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A Simple Combination Micromicroammeter and X-Ray Ionization Chamber

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OFTEN in advanced laboratory courses in physics there arises the need for an instrument capable of indicating currents as small as 10^{-11} amp. In these courses it is also quite likely that some elementary work may be done with x-rays. An ionization chamber, a virtual necessity for laboratory exercises using x-rays, requires an instrument sensitive to such small currents. It then becomes desirable to have an ionization chamber which utilizes a simple vacuum-tube amplifier capable of being detached for separate use as a micromicroammeter. College laboratory classes in advanced measurements, electricity, x-rays, modern physics, and physical chemistry, for example, might well benefit from having such a simple device for either direct x-ray measurements or for demonstrations of the powerful methods in scientific investigation made available by x-rays or ionization measurements. It is the purpose of this paper to describe such an apparatus.

For general laboratory use an x-ray tube may most simply be operated as a self-rectifying tube; i.e., with the tube connected directly across the high-voltage transformer secondary without benefit of rectifying apparatus. Such operation results in a pulsed x-ray output of power-line repetition frequency. The x-ray tube may also, of course, be operated from a high voltage rectifier, in which case the x-radiation will be continuous. An ionization chamber for use with both methods of x-ray operation would require an electrometer amplifier responsive to both d.c. and low frequency a.c. This quite naturally indicates the use of a direct-coupled amplifier. A simple, stable micromicroammeter using a d.c. vacuum-tube amplifier has been described in the literature[1] and this circuit has already been applied for a use quite similar to that being considered here.[2]

Most apparatus generally used in such applications is quite cumbersome. This instrument in addition to being small and portable is also inexpensive to build and easy to operate, all desirable features in an apparatus for student use. The equipment consists of a lead-lined sheet-metal box, measuring 14 in. high, 11 in. long, and 5 in. wide, weighing about 24 lb. This box contains the ionization chamber, electrometer amplifier, and associated power supplies. A remote indicating meter, contained in a separate, metal, sloping-panel meter case and connected to the main unit by a 10-ft shielded cable, has been provided to protect the experimenter from the direct x-ray beam. Figure 1 shows the entire apparatus. The upper section of the main unit contains a free-air ionization chamber. The side panels of the main unit, which may be removed for access to the ionization chamber, are provided with entrance and exit openings measuring 7 cm

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[1] Roberts, *Rev. Sci. Instr.* **10**, 181 (1939).
[2] Krebs and Kersten, *Rev. Sci. Instr.* **13**, 332 (1942).

on each side. The entrance aperture has a frame and spring clamp arrangement for holding variously sized lead diaphragms, and also for holding thin sheets of materials under investigation for absorptive qualities. This holder accommodates materials measuring 9×9 cm and in total thicknesses up to 2 cm. In the lower section of the main unit are contained the amplifier and power supply, which, as a sub-unit, plugs upward into the ionization chamber. The amplifier and power supply chassis may be removed from the bottom of the main unit, as shown in Fig. 2, for use as a sensitive micromicroammeter.

The case containing the main unit has been shielded with $\frac{1}{8}$-in. lead on the side panel receiving the incident radiation and also on the base supporting the collector (lower) electrode of the ionization chamber and separating this electrode from the amplifier unit. This thickness of lead has been found adequate for complete shielding from direct x-radiation of the intensities encountered in the normal use of the apparatus. The remainder of the case has been shielded by 1/24-in. lead to prevent any effect from scattered radiation. Electrostatic shielding, an important requisite for such a sensitive measuring device, has been achieved by constructing the case of sheet-metal, and by providing that this case must always be connected to ground before operation is possible. The entrance and exit openings have not been electrostatically shielded, such as with coarse metallic screening. No deleterious effects have been observed because of this omission, and an advantage is gained in the prevention of secondary radiation from any such screening.

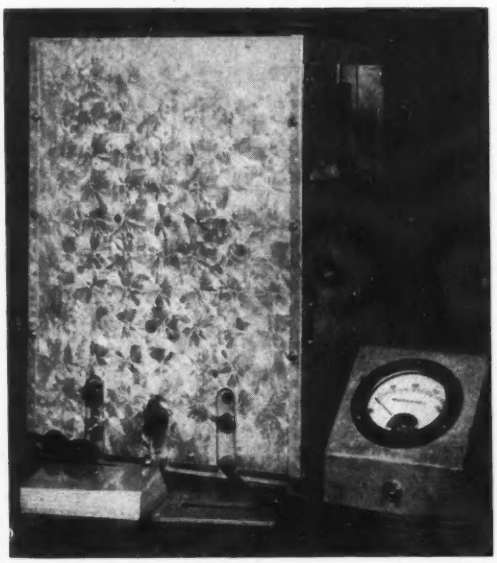

FIG. 1. Photograph of the entire apparatus, shown ready for use as an ionization chamber.

The Ionization Chamber

The ionization chamber has an irradiation volume of approximately 1850 cm³. The electrodes are $\frac{1}{8}$-in. aluminum sheets, measuring 21.2×8.7 cm and separated by 10 cm. The voltage electrode is suspended from the top of the case by four $\frac{5}{8}$-in. porcelain insulators, and voltage is supplied to it from the power supply through a long rod, extending downward from the ionization chamber base into the amplifier space, insulated from the bottom of the chamber, and having at its end a banana plug which fits into a recessed and insulated jack in the amplifier chassis.[3] The collector electrode is mounted in the bottom of the chamber space on five polystyrene rods, 1 in. high, located one at each corner and one at the center of the electrode. The central insulator, which is of about twice the diameter of those at the corners, contains a banana plug which is connected to the collector electrode and allows connection with the amplifier. The banana plugs project downward into the amplifier space so that connection may be made to appropriate parts of the amplifier chassis upon insertion of this unit into the bottom of the case. This particular mounting permits rigid suspension of the ionization chamber electrodes and, at the same time, easy removal of the electrometer-amplifier. Note the careful mounting of the collector electrode on superior insulation material to avoid unnecessary leakage resistance to ground. This is an extremely important consideration since the currents to be measured by this apparatus are less than 10^{-9} amp. Normal insulators conduct such current far too readily. A leakage resistance of 10^{11} ohms is the minimum

[3] Note that this represents a change from the arrangement shown in Fig. 2, where the rod is shown fixed to the amplifier-power supply chassis. This modification is considered a necessary safety precaution.

that can be tolerated; any less will seriously affect the accuracy of these measurements.

It has previously been mentioned that an aperture of 7×7 cm is available into the chamber, but this very large area is desirable only for extremely low energy radiation. In normal use it was found necessary to employ two diaphragms of $\frac{1}{8}$-in. lead plate which fit into the holder, one having an aperture 2×6 cm and the other 1×6 cm. These diaphragms are successful in preventing excess secondary wall radiation and serve to limit the indications on the meter to full-scale deflections.

Concerning the operation of the chamber, a saturation characteristic has been provided in Fig. 3. The chamber is operated at 400 v, so that operation in the saturated region is not assured for higher x-ray excitation voltages. It was not felt that saturation operation merited the increase in the size of the power supply for the required increase in voltage, particularly in view of the fact that satisfactory operation is still possible within the limits of accuracy of this instrument. Provision has been made, however, for front-of-panel connection to an external power supply if higher voltage operation be required.

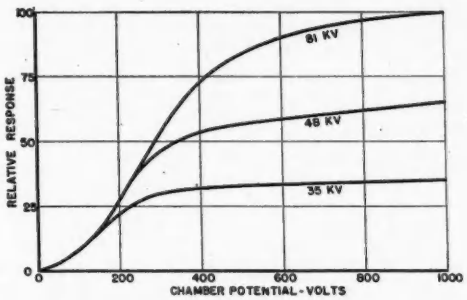

FIG. 3. Ionization chamber saturation characteristic. The chamber is normally operated at 400 v d.c.

The Amplifier

The theory and operation of electrometer tubes has been described elsewhere.[4] It is a well known fact that, with care in design and operation, ordinary amplifier tubes may be used as electrometer tubes. This fact has been used to advantage in the micromicroammeter used in this apparatus.[1] By connecting the ionization chamber collector electrode directly to the grid of the electrometer tube without benefit of the usual coupling capacitor it becomes possible for the amplifier to respond to steady ion currents as well as to pulsating ion currents, and also to utilize the very low ion currents in the most simple manner with minimum leakage. Another important feature of the Roberts circuit is the use of negative feedback, wherein the ability of the circuit to amplify is utilized, not to produce large voltage gains, but to provide small gains of great constancy and accuracy. This technique achieves stability of operation, independence from variations in the tube characteristics, and linearity of output voltage. The theory of the negative-feedback amplifier has been developed[1,4] and yields the interesting result that the current gain of the negative-feedback amplifier is determined by the ratio of the input resistance to the output resistance. In this application a high current gain is desired, of course. The accuracy of the instrument is then limited only by the indicating meter and the stability of the input resistance; all other factors have been eliminated.

A circuit diagram of the amplifier-power supply is given in Fig. 4. The d.c. amplifier consists of two tubes: a 12J7GT electrometer tube and a 6J5 used as a cathode follower. Negative feedback takes place from the cathode of the 6J5 to the grid of the 12J7GT when current flows through the meter as a result of meter circuit

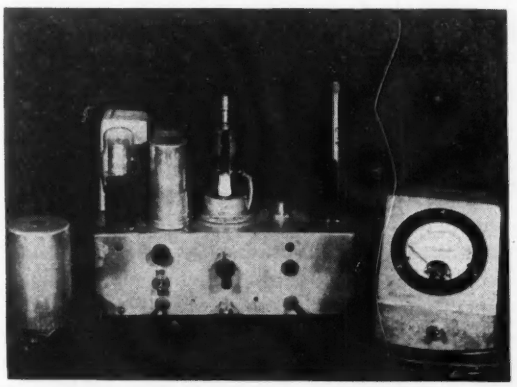

FIG. 2. Photograph of the amplifier-power supply chassis, shown ready for use as a micromicroammeter. The electrometer tube shield has been removed to show constructional details.

[4] Reich, *Theory and application of electron tubes* (McGraw-Hill, 1944, ed. 2), pp. 612–616.

unbalance. The 12J7GT cathode bias potentiometer has been called the "Zero Adjust" control, since its control over the bias of the electrometer tube permits the balancing of the amplifier so that, for no input, the indication of the microammeter will be zero.

It will be of value to determine the current gain of the amplifier. As stated above, the current gain is determined by the ratio of the input to the output resistance. Referring to Fig. 4, it may be seen that the input resistance is 10^9 ohms and the output resistance is 5000 ohms; hence, the designation "Calibrate-Sensitivity" control for the latter. Normally, this control will be set for about 2500 ohms. Thus the current gain will be 4×10^5. Now the output current is that indicated on the 200 μa meter, which has a least count of 5 μa, so that the least count will correspond to 1.25×10^{-11} amp ionization current. By definition, 1 amp is equivalent to 3×10^9 statcoulomb sec^{-1}, which means that the least count of the meter represents 3.75×10^{-2} statcoulomb sec^{-1}. The approximate definition of the international unit of radiation intensity, the *r*-unit, is the quantity of radiation which produces in 1 cm^3 of atmospheric air at standard conditions such a degree of conductivity that one electrostatic unit of charge is measured at saturation current. So, to obtain the approximate meaning of the meter least count in terms of radiation intensity, recall that the ionization chamber has a volume of 1850 cm^3. Because of the 7×7 entrance aperture, however, the irradiated volume will be about 1700 cm^3. Thus, the least count indicates:

$$\frac{3.75\times10^{-2}\ \text{statcoulomb sec}^{-1}}{1700\ \text{cm}^3}=2.2\times10^{-5}\text{r sec}^{-1}.$$

The maximum intensity, indicated with 1-ma full-scale meter deflection, as provided by a meter shunt, corresponds to:

$$4.4\times10^{-3}\ \text{r sec}^{-1}\quad\text{or}\quad 0.26\ \text{r min}^{-1}.$$[5]

In considering the linearity and accuracy of the circuit, tests have shown that all deviations have been less than 4 μa, or ±2 percent, the tolerance of the indicating meter. The only other consideration in the accuracy of the instrument is the stability of the high input resistance. According to the manufacturer, resistance changes due to high humidity will not exceed ±3 percent, while the temperature coefficient is negligible. It may then be concluded that the instrumental error is about ±5 p ent.[6]

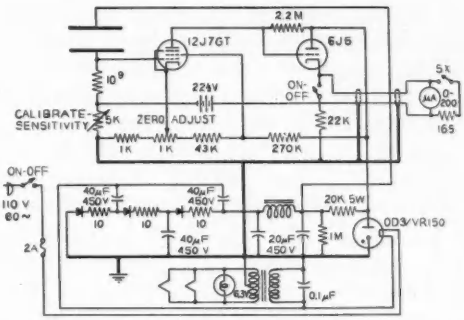

FIG. 4. Schematic diagram of the amplifier-power supply.

In Fig. 2, the details of the electrometer mounting may be seen. The banana plug from the ionization chamber collector electrode fits into a brass cylinder which slips over the 12J7GT grid cap. One terminal of the high resistance is connected to this cylinder. In the photograph, this resistor is the vertical rod parallel to and in front of the electrometer tube. It is supported from the tube base on a porcelain insulator. Thus the only leakage paths shunting the high resistance are provided by the following objects: the polystyrene supports of the ionization chamber collector electrode, the surface of the electrometer tube, the internal supports of the grid of the tube, and the surface of the high resistance. These represent the practical minimum.

The electrometer tube and high resistance are themselves enclosed in a cylindrical aluminum shield to eliminate further the effects of stray electrostatic fields. This shielding is highly effective. In addition, all wiring in the amplifier has been done with shielded cable and only cased or shielded components have been used wherever practicable. Every precaution must be taken to eliminate all effects of stray fields.

The indicating meter has been provided with a shunt which, when the switch is closed, serves

[5] With the 2×6 cm and 1×6 cm diaphragms these values will be increased by a factor of 4 and 8 times, respectively.

[6] When using the apparatus as an ionization chamber, this error assumes the chamber operated at saturation voltage.

to multiply the readings by five. It is to be noted that, because of the polarity of the voltage applied to the amplifier from the ionization chamber, the voltage across the 6J5 cathode follower load resistor may go to zero when a large enough input voltage cuts off the cathode follower. At cut-off the meter will read about 0.86 ma because of the values of the meter circuit constants. The multiplying factor is thus determined by this maximum. The maximum reading may be increased by using a smaller cathode load resistor, but this maximum range has been found sufficient for the instrument.

The Power Supply

The power requirement of the apparatus is 115 v, 60 cycle sec^{-1} at $\frac{3}{4}$ amp. The power supply furnishes outputs of 400 v d.c. for the ionization chamber, 150 v d.c., regulated, for the amplifier, and 6.3 v a.c. for the amplifier heaters. The high voltage is supplied by a half-wave voltage tripler using small selenium plate rectifiers in place of the usual vacuum tubes. These units make possible very compact, high voltage, moderate-current power supplies. In series with the rectifiers are 10-ohm current-limiting resistors for protection of the rectifiers against current overload.

The 115 v a.c. input circuit requires special consideration. The extreme requirement for electrostatic shielding has been mentioned repeatedly. In order to assure adequate grounding of the entire unit, a special a.c. input has been used. The a.c. line plug has only one prong. When this plug is inserted into an a.c. socket, one of two conditions will prevail. Since the a.c. line is always grounded on one side and at 115 v above ground on the other side, either 0 v or 115 v will be supplied to the unit. If the case is not grounded, there will be no return circuit. When the case is grounded it is possible that 0 v will be applied, or that 115 v will be applied, finding a return path through the grounding lead. Thus the case must be grounded before the unit can operate. To determine the proper line plug polarity, the power switch is turned on, which causes the indicating meter to show a deflection because of the internal battery. This shows that power may enter the unit. The line plug prong is now inserted in each of the socket terminals, the proper polarity being indicated by the illumination of the pilot light, showing that power is being supplied.

The input power passes through a 2 amp fuse, required by the initial high current surge through the rectifiers, through the jumper in the base of the 0D3/VR150 regulator tube and out to the heater transformer and rectifiers to ground. The input power circuit through the regulator tube requires the presence of this tube in the high voltage circuit so that no more than 150 v can ever be applied to the amplifier tubes.

Operation of the Apparatus

A step-wise outline will now be given to provide detailed directions for placing the apparatus in operation:

1. Place the main unit in position to receive the direct beam of the x-rays. The tube-to-unit distance will be dependent upon the circumstances of the measurement or upon the radiation intensities desired.

2. The x-ray beam should be limited by means of a diaphragm at the x-ray tube so that only part of the area of the chamber aperture will be irradiated. The ionization chamber diaphragm may be selected after the unit is in operation.

3. Connect the main unit to ground by means of the terminal provided on the front of the unit.

4. Place the power switch in the "ON" position. The indicating meter should show a deflection.

5. The a.c. line plug may now be inserted in a socket. If the polarity of the plug is correct, the pilot light will be illuminated, and the amplifier will be in operation. If not, merely reverse the position of the plug. No indication for either position will usually mean that the internal fuse has been blown.

6. Immediately upon application of the power, the meter indication will go off scale in the negative direction. After about one minute the meter may return on scale. Regardless of this, it will now be possible to adjust the meter reading to zero with the "Zero Adjust" control on the front panel. A total warm-up period of at least two minutes should be allowed before stabilization of the amplifier may be considered achieved and zero adjustment attained.

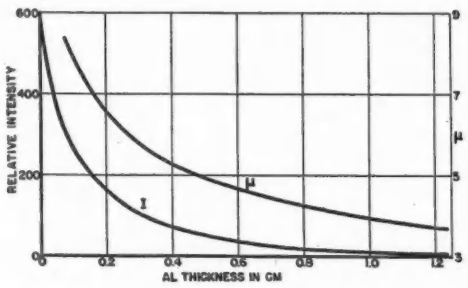

FIG. 5. X-ray absorption curve for aluminum at 48-kv peak, self-rectifying. The absorption coefficient, μ, is determined from the equation $I = 585e^{-\mu t}$.

7. The apparatus is now ready for use. Indications of the meter are of the relative intensity of the x-radiation. The switch provided on the panel of the meter permits multiplication of the meter indication by a factor of five.

Applications of the Instrument

The primary purpose for which this instrument has been designed is the comparison of x-ray intensities. Several applications are possible: x-ray dosage determination, x-ray absorption investigation, x-ray quality measurement, and measurements of very minute electric currents.

If care is exercised in operating the ionization chamber only in the saturated region, calibration in terms of *r*-units is indeed possible. The "Calibrate-Sensitivity" control, a screwdriver adjustment located on top of the amplifier-power chassis, may be set so that the meter will indicate over a certain desired range of radiation intensity. The standard for calibration may be obtained either from a known quantity of radioactive chemical or by comparison with a clinical x-ray dosimeter which has itself been previously calibrated. Hospitals equipped for radiation therapy are usually able to provide either or both standards. This instrument, when calibrated, should not be relied upon for accuracies better than 5 percent, however.

Using the holder provided on the entrance panel of the apparatus, it is possible to insert various materials in the path of the incident radiation for the purpose of measuring the absorption of x-rays. Here the indications of the meter are directly proportional to the amount of radiation transmitted. Generally thin sheets of metals are available for interposition in the beam of x-rays. Heavily absorbing materials, such as lead, may be utilized by fastening a foil on light cardboard which is virtually transparent to the beam. Figure 5 shows a typical absorption curve.

With two such instruments, one behind the other in the beam, measurements on the absorption of gases may be obtained. This is a standard practice for materials that require extreme absorbing thicknesses.

In designing the apparatus, particular means have been employed to allow the separate use of the amplifier for the measurement of very minute electric currents. By removing the amplifier-power supply chassis from the case, a small, convenient, electrometer-type amplifier is thereby made available. It has earlier been shown that full-scale deflection of the meter (200 μa) corresponds approximately to 5×10^{-10} amp, and that the response of the amplifier and thus the indications of the meter are linear with respect to the applied voltage and hence, with respect to the current passed through the input grid resistor. The electrometer tube and input resistor have been carefully shielded to prevent external electrostatic influence, and the input leakage path has been reduced to the absolute minimum. Connection to the input of the amplifier may be simply achieved by the insertion of a banana plug into the jack on top of the electrometer tube. Calibration will, of course, be necessary, and this can readily be achieved by means of the "Calibrate-Sensitivity" control.

Believing, as I do, in the continuity of nature, I cannot stop abruptly where our microscopes cease to be of use. Here the vision of the mind authoritatively supplements the vision of the eye.—JOHN TYNDALL.

High Energy Accelerators at the University of California Radiation Laboratory

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THIS is the first of a series of four articles describing recent research in high energy nuclear physics at the University of California Radiation Laboratory in Berkeley. The term "high energy" is used here to distinguish the energy region above about 20 Mev from that below, the latter having sometimes been called the region of "classical nuclear physics." This dividing line has a manifold theoretical significance which will be made clear in the subsequent articles. Experimentally, 20 Mev is also about the energy at which relativistic effects begin to be noticeable in problems of acceleration. The adjectives "high energy" and "relativistic," in reference to nuclear particles, will be used interchangeably in these articles.

It seems appropriate, in an account of the high energy physics research at the Radiation Laboratory, to begin with a description of the three new accelerators which are the basic tools. These are the proton linear accelerator, the 184-inch synchrocyclotron, and the synchrotron. All three have been in operation for less than three years. The other operating research accelerators at the Radiation Laboratory are nonrelativistic cyclotrons of a design which has been widely publicized. They will not be described again here.

All practical accelerators depend upon the possession of an electric charge by the particle which is to be accelerated. The force $\mathbf{F}$ on a particle with charge e in an electromagnetic field is given by the Lorentz equation

$$\mathbf{F}=e[\mathbf{E}+(\mathbf{v}/c\times\mathbf{H})], \qquad (1)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic fields in cgs units, $\mathbf{v}$ is the velocity of the particle, and c is the velocity of light. An electric field is, therefore, required to increase the energy of a particle, but a magnetic field can be used to curve the orbit in a particularly convenient way. The electric field may in some cases, as for instance in the betatron, be produced by a changing magnetic field.

In using Eq. (1), the relativistic mass of the particle must be employed if the velocity v is not small compared with c. Thus, if we wish to write $\mathbf{F}=d(m\mathbf{v})/dt$, the mass must be understood as

$$m=m_0(1-v^2/c^2)^{-\frac{1}{2}}, \qquad (2)$$

where m_0 is the rest mass. The relativistic mass increase is not very important for the proton linear accelerator but it dominates the operation of the other two machines.

For each accelerator there will be three main topics of interest: (1) The geometrical configuration which allows a particle to fall through a "potential difference," $\int\mathbf{E}\cdot d\mathbf{s}$, producing its final energy. (2) The focusing and stability characteristics of the beam. (3) The performance of the machine, that is, its capabilities as a research tool. The second point is usually passed over in qualitative discussions, although it is of crucial practical importance. Focusing and stability will receive a considerable share of our attention.

The Berkeley Proton Linear Accelerator [1]

The name "proton linear accelerator" is descriptive and accurate. This machine accelerates protons in a straight line, producing a collimated monoenergetic external beam. The general principles upon which the Berkeley linear accelerator is based have been understood for twenty years. Wideröe in 1929 constructed a two-gap linear accelerator based on an idea of Ising's,[2] and Sloan and Lawrence[3] built a multi-gap machine in 1931 which successfully employed a radiofrequency electric field to accelerate mercury ions. Nevertheless, there was a general feeling before World War II that radiofrequency linear accelerators would never be appropriate for nuclear research. To accelerate nuclear particles in this way to energies in the million volt region required far higher power than was then available at short wavelengths. The great success of the cyclotron

[1] This section is largely abstracted from a complete report by L. W. Alvarez, H. Bradner, H. Gordon, W. K. H. Panofsky, C. Richman, and J. R. Woodyard, to be published in the *Review of Scientific Instruments*.

[2] Wideröe, *Arch. f. Elektrotechnik* **21**, 387 (1929). G. Ising, *Arkiv. för matematik, astronomi o. fysik.* Bd. **18**, No. 30, 1 (1924).

[3] Sloan and Lawrence, *Physical Rev.* **38**, 2021 (1931).

FIG. 1. Electric lines of force of the Berkeley proton linear accelerator; side view of tank.

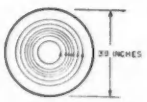


FIG. 2. Magnetic lines of force of the Berkeley proton linear accelerator; end view of tank.

made the prospect of a competitive linear accelerator seem small indeed.

During the war, the main technical bars to the construction of linear accelerators were removed. Radar research led to the development of vacuum tubes capable of producing megawatts of pulsed radiofrequency power down to the microwave range. It seemed, too, as if an upper limit at around 100 Mev to the energy attainable by cyclotrons would soon be reached. We shall see later that this difficulty was circumvented, but at the time it led to a reawakening of interest in linear accelerators, which possessed no such limitation. At Berkeley, L. W. Alvarez was the chief supporter of the "linac," and he supervised the construction of the present 40-ft machine. The Berkeley accelerator was actually originally designed as a pilot model for a machine which might eventually reach the billion volt energy region! An extension to the 200–300-Mev range may still be made, but at present, the original plans have been dropped in favor of the "bevatron" or proton synchrotron. The 40-ft accelerator is being used now as a research tool.

General Description of the "Linac."—A direct quotation from reference 1 will serve as a basis for describing the machine. "The accelerator consists of a cavity 40 feet long and 39 inches in diameter, excited at resonance in a longitudinal electric mode with a radiofrequency power of about 2.5 megawatts peak at 202.5 megacycles. Acceleration is made possible by the introduction of 46 axial drift tubes into the cavity, which is designed such that the particles traverse the distance between the centers of successive tubes in one cycle of the r-f power."

If the drift tubes are temporarily ignored, one has, therefore, a large cylindrical cavity with copper conducting walls in which a standing electromagnetic wave is set up. In the particular mode chosen, the electric field is parallel to the axis of the cylinder, its magnitude being a maximum at the center of the tank and falling to zero at the radial walls. The electric field, in this simplified situation, does not vary along the axis of the cylinder.

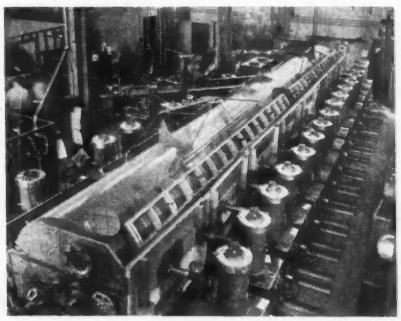
At any instant, the lines of electric force would look as in Fig. 1, with an amplitude varying sinusoidally in time. (The instantaneous power flow, however, is radial not longitudinal.) The frequency ω is easily calculated, since the situation is exactly like that of a circular membrane, where

$$\omega/c = 2.4/\text{radius}.$$

Here c is the velocity of light, so we find, for the period

$$T = 2\pi/\omega = 2.62 \text{ radius}/c = 4.3 \times 10^{-9} \text{ sec},$$

or a frequency of about 230 megacycles. The



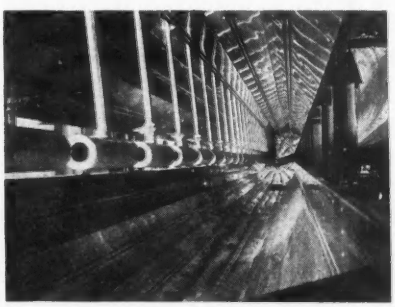


FIG. 3. (a) External view of the Berkeley linear accelerator. Input is at near end, the Van de Graaff being to the left just outside the picture. (b) Interior of "linac" tank showing drift tubes.

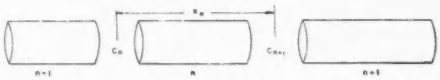


FIG. 4. Drift tube configuration, showing the distance a proton must travel in one period of the electric field oscillation in the Berkeley proton linear accelerator.

actual resonance frequency, quoted above, is lower because of the presence of the drift tubes.

There is, of course, at all times in this mode a magnetic field perpendicular to the electric. The magnetic lines of force are circumferential, as shown in the cross section of the cavity, Fig. 2. The magnetic intensity on the axis is zero although it does not vanish on the radial walls. It plays no direct role either in the acceleration or focusing of the protons since they must travel near the axis and never acquire extreme relativistic velocities. The cavity is excited, however, via the magnetic field, whose time variation is then responsible for the electric field.

The scheme of acceleration is now clear. Protons are introduced into one end of the tank on the axis. When the electric field is in the correct direction, the protons are accelerated along the axis. If the protons could traverse the entire length of the cavity in half a period, i.e., before the electric field could change sign, there would be no need of further complications. It turns out, however, that about 46 periods are required to make the trip, so 46 "drift tubes" are introduced along the axis to shield the protons from the adverse half-cycles of the electric field. A photograph of these drift tubes is shown in Fig. 3b. They are simply cylindrical sections of a heavy copper tube, cut in appropriate lengths. Their presence in the cavity modifies the electromagnetic field so that the crude considerations given above do not suffice for the actual problem of design. For more detail, readers are referred to the complete report.[1]

The question naturally arises as to what limits the amplitude of the electric field along the axis when there is a supply of power to the cavity. The answer is that the copper cavity walls are not perfect conductors and that there is a flow of energy into the walls which is dissipated as heat. When this power loss equals the power input, the electric field has reached its maximum amplitude. Putting it the other way around, the value of the desired electric field amplitude determines the power input required. In practice, power is supplied in pulses, not continuously, and it turns out that for a fixed electric field amplitude the energy required per pulse is inversely proportional to the square of the resonance frequency. Since the cost of important portions of the equipment is proportional to the energy per pulse, the advantage of a high frequency is obvious. High frequencies, of course, mean small cavity radii, and the limit is set by the question of geometrical aperture as well as by availability of equipment.

Stability of the Linac Beam.—The very important question of beam stability has two quite different aspects, which will be called "phase focusing" and "radial focusing," respectively. Phase focusing refers to those restoring forces which act in the longitudinal direction and tend to keep the protons arriving at the successive gaps at the proper time or "phase" with respect to the oscillations of the electric field. Radial focusing has to do with the radially acting forces which keep the protons on or near the axis of the cavity.

It is clear that the centers of two successive gaps between drift tubes must be separated by just the distance which a proton will traverse in one period of the electric field oscillation. Thus, if the average velocity of the proton in the nth drift tube is v_n,

$$x_n = v_n T,$$

where x_n is defined in Fig. 4 and T is the oscillation period. The drift tubes at the exit end of the cavity are, therefore, longer than those at the input end in the ratio of exit to input proton velocity. Even with this condition satisfied, a

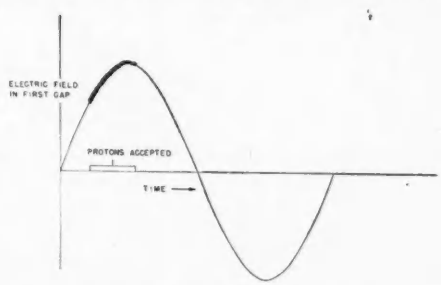


FIG. 5. Time variation of the electric field, showing the interval during which protons can be accepted for stable acceleration in the Berkeley proton linear accelerator.

FIG. 6. The electric field between drift tubes, without grids or foils in the Berkeley proton linear accelerator.

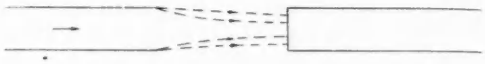


FIG. 7. The electric field between drift tubes when a conducting grid or foil is placed across the tube entrance in the Berkeley proton linear accelerator.

negligible number of protons could stay in correct phase for the whole 46 cycles if there were no phase focusing. It will be recalled that the electric field is not constant in time as the proton crosses a gap. Suppose that a proton passing C_n (Fig. 4) at the correct time is going slightly faster than the velocity for which the tube length and separation were designed. The proton will arrive at the next gap too soon and will consequently encounter an electric field which is either stronger or weaker than had been intended, depending on whether the field is decreasing or increasing. If the field is stronger, the proton's velocity is thrown even farther out of line, and it eventually falls completely out of phase. If the field is weaker, however, the proton receives a smaller kick than normal so that its velocity after crossing the gap is closer to the selected value than before. An analogous situation exists if the proton starts out too slow, with all statements just reversed. Again it is the increasing field which "bunches" and the decreasing field which "debunches" the protons; so that of the half-cycle during which the electric field is in the correct direction for acceleration, only the increasing portion can be used.

We can define the proton's phase at the nth gap $\phi(n)$ as the difference between its actual arrival time at C_n and the selected time for this arrival, expressed in radians. From the arguments of the above paragraph we see that the selected time must be during the quarter-cycle which has a positive and increasing field. If the proton is injected into the first gap with a velocity not too far from the proper value and with only a small phase $\phi(1)$ then during the passage through the cavity its phase will oscillate about zero due to the continuous restoring influence described above. In the 40 ft of acceleration there will be about two such phase oscillations. The largest permissible initial phase amplitude depends on the selected time. It is about 30° in actual operation, when the selected phase is 20° before the maximum (see Fig. 5).

The second stability problem concerns radial oscillations. What forces are there to keep the protons in a narrow beam along the axis of the cavity? It has already been pointed out that the magnetic field has negligible influence. If there were no radial components in the electric field, one might hope to inject a well focused beam and get it back again at the output end. The field between drift tubes necessarily has a radial component for any point off the axis, however, just because the longitudinal component has to vary along the axis. In other words, the condition, div $E=0$, requires $\partial E_r/\partial r$ to be nonzero if $\partial E_z/\partial z$ fails to vanish. We know that E_z, the longitudinal component, is zero inside the drift tube and nonzero in the gap. Consequently, if the radial component E_r is zero on the axis, it is not zero a finite distance away from the axis and may be such as to either focus or defocus the beam radially. It can be proved that unless a grid or foil is introduced across the entrance end of the drift tubes, the radial field defocuses when the conditions are correct for stable phase oscillations. Qualitatively, this point can be understood as follows: The electric lines of force between drift tubes look roughly as in Fig. 6, in the absence of foils or grids. The first half of the gap is a focusing region and the second half defocusing. The electric field intensity must be increasing with time, however, to achieve phase stability, and this means that the second half of the gap outweighs the first. The net effect is defocusing. This simple argument is only true if the fractional increase in proton velocity per gap is small so that the time spent in each half of the gap is about the same.

The only way to avoid this defocusing is to introduce charge into the beam, allowing the electric lines of force to end abruptly without swinging out again. This can be done by means of a grid or foil across the entrance of each drift tube. In the new situation the lines of force may look as in Fig. 7, so that the net effect now is one of focusing.

At the time the linear accelerator was planned, it was thought that foils were more desirable than

grids, since the latter give an exponential attenuation with increasing number. Consequently, an injection energy of 4 Mev was used, in order to bypass the problem at low energies, where multiple scattering in the foils would attenuate the beam seriously. (Multiple scattering increases rapidly with decreasing energy.) The 4-Mev injection beam was obtained from a pressure Van de Graaff generator of conventional design. Actual tests showed later that foils were destroyed by sparking in the tank, and grids replaced them with apparently just as good focusing properties. The present grids are extremely transparent, the whole set of 46 removing only about half the beam. Since the multiple scattering problem does not exist with grids, it would now be possible to inject at a much lower energy. (The grid attenuation in a long machine could be eliminated by changing over to foils at high energy, where the scattering loss is small.) However, the Van de Graaff generator is working so well that the *status quo* will be maintained.

Linac Performance.—In June, 1949, the performance of the Berkeley proton linear accelerator was as follows: Power was supplied to the cavity in pulses 30 times per second, each pulse lasting 600 microseconds, of which 525 microseconds were useful, i.e., at maximum field amplitude. A fraction, 1/30, of the 1.0-milliampere injection current from the Van de Graaff was accepted for acceleration, and of this, about one-half was removed by the grids. What remained amounted to an average current of 0.25 microamperes, or a peak current of 16 microamperes during the pulses. The average energy of the emerging protons is between 31.5 and 32 Mev, with a spread of less than 100 kev (0.3 percent). The beam is very well collimated, about 85 percent passing through a circular hole $\frac{1}{8}$ inch in diameter. The angular divergence is 10^{-3} radians.

As far as reliability of operation is concerned, there were only three openings of the tank for repairs involving leaks, etc., during the first year of operation. Time lost in repairing the power supply units was negligible. Originally the main source of trouble was the Van de Graaff generator, but this is now very reliable. The machine is operated 16 hours a day, 6 days a week, with beam available 85–90 percent of the time. At present a modification is under way which, it is hoped, will raise the average current by a factor of more than 10. The fraction of the injected beam which arrives in an acceptable phase will be increased by an appropriate bunching of the protons before they enter the cavity, in the manner employed in klystrons. Two large oscillators will eventually replace the 27 now used. This will involve only four vacuum tubes instead of 108.

The performance of the linear accelerator, for proper evaluation, must be compared with that of the synchrocyclotron, to be described next. The average *external* beam will be seen to be 5000 times stronger and the pulses 40,000 times as long, although at a much lower energy. The proposed extensions of the linear accelerator should be able to overcome the energy discrepancy while still maintaining the advantage in intensity and pulse length.

The 184-Inch Synchrocyclotron

Before the last war, work had begun at Berkeley under the encouragement of E. O. Lawrence on what was thought of then as a giant accelerator. The object was to push to the limiting energy permitted by the cyclotron principle. The basis of conventional cyclotron operation is the fact that the orbital period of an ion circulating in a uniform magnetic field is independent of the velocity so long as the latter is small compared with c. The period is given by

$$T=(2\pi mc)/(eH), \qquad (3)$$

which can be derived from Eq. (1). Thus, an electric field across a diametral gap, which oscillates with just this frequency, will always find the ion in the correct phase to be accelerated if it started in this phase. One would expect the maximum energy attainable for a fixed magnetic field to be set only by the outer radius of the cyclotron (the orbital radius expands in proportion to the ion momentum), and to be independent of the amplitude of the applied electric field. However, in Eq. (3) the mass appears, which means that as the velocity of the particle increases the corresponding mass increase will cause the period to lengthen. If too many circulations in the cyclotron are required and too high a velocity acquired, the ion will eventually fall out of phase with the electric field and no longer be ac-

celerated. To reach a high energy, therefore, the applied electric field must be so strong that not many circulations are necessary. The original plans for the 184-inch Berkeley cyclotron envisaged a dee voltage of one to two million volts! This necessitated a very large magnetic gap and gave promise of extraordinary difficulties. Even so, the maximum energy for deuterons was to be only 70 Mev. To go higher seemed impossible.

After the war work on the big machine was resumed under the supervision of R. L. Thornton, but before completion, E. M. McMillan[4] at Berkeley and V. Veksler[5] in Russia independently proposed a scheme to remove the upper limit on the energies attainable and eliminate the need for large dee voltages. The scheme is based on the existence of phase stable orbits, and since not only the synchrocyclotron but also the electron synchrotron and the proposed bevatron or proton synchrotron depend on this principle, it is worthwhile to devote a separate section to it.

The Principle of Phase Stability.—The increase of orbit period with velocity, which was an undesirable feature in the conventional cyclotron, actually makes the phase stable orbits possible. In direct contrast to the linear accelerator, the faster a particle goes in a cyclotron, the longer it takes to make the trip between successive gaps. This is because the radius of curvature increases and the longer path more than compensates the increased velocity. Therefore, the same type of argument that was applied to the "linac" will in this case show that if the ion arrives at the gap

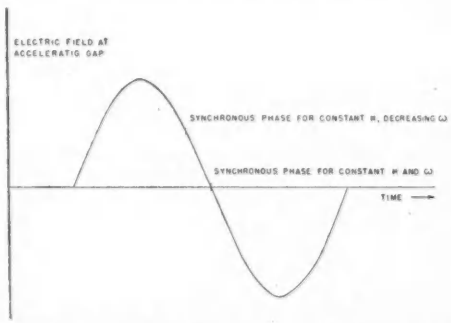

ELECTRIC FIELD AT ACCELERATIG GAP
SYNCHRONOUS PHASE FOR CONSTANT H, DECREASING ω
SYNCHRONOUS PHASE FOR CONSTANT H AND ω
TIME

FIG. 8. Time variation of the electric field at the accelerating gap of the 184-inch Berkeley synchrocyclotron, showing two possible positions of the synchronous phase.

when the electric field is *decreasing*, phase stability can result. This means that for a fixed magnetic field H and a fixed frequency ω of the electric field, an ion of mass near

$$m = eH/(\omega c)$$

or total energy near

$$E = mc^2 = Hec/\omega \tag{4}$$

can revolve indefinitely in a cyclotron orbit with the appropriate radius. If its energy is momentarily larger than the resonance value above, it arrives at the gap later, relative to the phase of the gap voltage, on each successive turn and eventually finds a retarding field to slow it down. If the energy is smaller than the resonance value, the reverse is true. The "synchronous phase" in this case, about which the phase of the ion will oscillate, corresponds to that time at which the electric field is zero, going from positive to negative. (See Fig. 8.)

Clearly the ion, on the average, gains no energy from the electric field and the amplitude of the latter can be very small. If now H is increased and/or ω decreased by a small fractional amount, the resonance energy increases by a correspondingly small amount. The ion is able to readjust itself and will oscillate about the new energy. In the process it has gained some energy from the electric field; and if the small changes in H or ω continue, the energy of the ion can be increased indefinitely. It is necessary, of course, to have a very good vacuum in the cyclotron tank so that in the course of this long trajectory the ions are not scattered.

Bohm and Foldy[6] have given a complete discussion of the phase oscillations in which they point out the analogy to a pendulum which is acted upon by a constant torque. A given rate of change of the magnetic field or the frequency corresponds to a certain rate of increase of energy which must be supplied by the electric field. This is the external "torque" and it displaces the synchronous phase (or rest point of the pendulum) as shown in Fig. 8. If the initial displacement of the ion phase from this rest point is not too great, it will execute oscillations with an amplitude which decreases with increasing energy. An ion

[4] E. M. McMillan, *Physical Rev.* **68**, 143 (1945).
[5] V. Veksler, *J. Physics U.S.S.R.* **9**, 153 (1945).
[6] D. Bohm and L. Foldy, *Physical Rev.* **70**, 249 (1946).

once trapped in a stable orbit will stay trapped. The only problem is to get it properly started.

That the phase stable orbits could actually be used to accelerate an appreciable number of ions was proved in 1946 by experiments on the old 37-inch Berkeley cyclotron.[7] Although the maximum energy was only 7 Mev, this was achieved with a peak potential across the gap of 3 kev! The time average current was 0.2 microampere. This is adequate for many purposes, even though several hundred times less than can be achieved by conventional continuous operation. The relativistic mass increase expected at higher energies was simulated by causing the magnetic field intensity to fall off radially. This was then compensated by decreasing the frequency of electric field oscillation during the acceleration. As expected, there was no appreciable change in the number of ions in a pulse during the 5000 revolutions required. The limitation on the current lay in the ability of the ion source to deliver at the right place and in the right phase at the start.

General Description of the Synchrocyclotron.[8]—When it became evident that a dee voltage of only a few tens of kilovolts would be adequate, it was possible to modify the design of the 184-inch cyclotron so as to reach more than twice the energy originally hoped for. The magnetic gap could be reduced to 19 inches, allowing a field of 15,000 gauss at the center. To achieve the synchronous operation, it was necessary to modulate the frequency and not the magnetic field, since the magnet (already built) was not constructed of laminated iron. The required frequency variation was obtained from a rotating condenser which modulated the capacitance of the oscillator circuit.

With the stronger magnetic field and the possibility of utilizing almost the full radius, the following maximum particle energies have been achieved: 190 Mev for deuterons, 380 Mev for alpha-particles, and 350 Mev for protons. The dee voltage usually employed is 20 kev but this figure is not at all critical. Each ion makes about 10^4 revolutions, picking up 7 or 8 kev each time around and taking about a millisecond to complete its total trajectory. The cycle is repeated 120 times a second, the ion source at the center being pulsed to coincide with the start of each cycle.

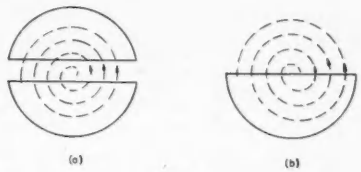


FIG. 9. (a) Dee configuration in conventional cyclotron. (b) Dee configuration in Berkeley synchrocyclotron.

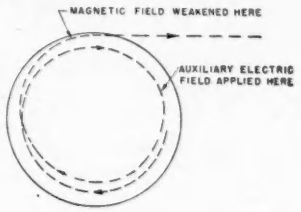


FIG. 10. Schematic drawing of deflection scheme to obtain external beam from 184-inch synchrocyclotron.

Because electric focusing is so inconsequential in the 184-inch machine (see next section), it was possible to have only a single dee rather than the double dee arrangement of a conventional cyclotron (see Fig. 9). This is a welcome simplification and facilitates access to the tank. The height within the dee available to the beam is five inches.

The deflection scheme which can be used to get part of the circulating ions outside the tank is quite interesting. When a group of ions has reached its maximum radius (about 81 inches, see next section), it can be given a radial kick by an auxiliary electric field. This displaces the center of the orbit, as in Fig. 10. The next time around the ions come much closer to the outer edge of the pole faces and encounter a region where the magnetic field has been intentionally weakened. They can then escape down a specially constructed channel through the shielding. The resulting pulse has a duration of $\sim 10^{-8}$ sec. This elaborate scheme is necessary because of the close spacing of successive turns, precluding the possibility of "peeling off" an outer orbit as in a conventional cyclotron deflector.

Injection and Stability of the Synchrocyclotron Beam.—It has already been pointed out that the beam is phase stable and that the main problem is the injection. Bohm and Foldy[9] have made a

[7] J. R. Richardson, K. R. MacKenzie, E. J. Lofgren, and B. T. Wright, *Physical Rev.* **69**, 669 (1946).

[8] W. M. Brobeck, E. O. Lawrence, K. R. Mackenzie, E. M. McMillan, R. Serber, D. C. Sewell, K. M. Simpson, and R. L. Thornton, *Physical Rev.* **71**, 449 (1947).

[9] D. Bohm and L. Foldy, *Physical Rev.* **72**, 649 (1947).

detailed theoretical study of the injection difficulties in order to determine the synchronous or equilibrium phase which maximizes the efficiency of capture into the portion of the r-f cycle giving phase stability. If the equilibrium phase is too great, measured from the time when the field goes through zero, the capture efficiency is limited by the narrow range of phase stability. (See Figs. 8 and 9.) If the equilibrium phase is too small, the orbital radius expands so slowly that the ions may return to the center in their first radial oscillation (see below) and be lost. The optimum phase, both theoretically and experimentally, turns out to be near 30°. This corresponds to a capture efficiency of the order of 1 percent.

The radial and vertical "free oscillations" in the synchrocyclotron are stable by virtue of the magnetic field design. The adjective "free" is used to distinguish these motions from the slow radial oscillations which are due to small variations in the energy of the particle. The free oscillations have a frequency which is comparable to the frequency of rotation, while the phase oscillations have a period long compared to that of rotation. Therefore, the two can be considered independently. The condition for the stability of free oscillations is the same as in the betatron or synchrotron or in any machine in which the electric focusing is negligible: The vertical magnetic field intensity must fall off radially. From the Maxwell equation, $\text{curl}\mathbf{H}=0$, one can easily prove that this implies a radial component which quenches any attempt by the ion to leave the median plane. In the 184-inch synchrocyclotron, the magnetic field intensity decreases linearly to a radius of 80 inches, where its value is 95 percent that at the center. From that point on it decreases much more rapidly, so that the beam actually "gets lost" at 81 inches, due to a coupling between radial and vertical oscillations. The latter will invariably occur if the field intensity decreases too fast. The shaping of the magnetic field is accomplished by the appropriate placing of shims inside the vacuum chamber.

Performance of the Synchrocyclotron.—The time average internal current is about 0.9 microamperes for protons and deuterons, and somewhat less for alpha-particles. If it is necessary to bring the beam out, a factor of ten thousand is lost. Operation can be changed from one type of ion to another in only a few minutes. Because of the moderate dee voltage, problems of sparking and electrical breakdown in the tank are greatly reduced. Also the natural stability of the synchronous operation makes it unnecessary to maintain a critical relation between the frequency and magnetic field. For such reasons the internal beam operation is remarkably steady, often showing many minutes of operation without sparking or beam variation of more than a few percent. Access to the internal beam for experiments is obtained through vacuum locks so as to avoid loss of the tank vacuum condition.

The percent of time in which the cyclotron is available for operation has consistently averaged over 90 percent and for one month's period was 97 percent. The percentage of time during which the beam was actually operated has averaged about 60 percent, the difference being accounted for by experimental set-up times, target changes, etc.

The Synchrotron, An Electron Accelerator

The acceleration of electrons to energies of the order of Mev and higher poses quite a different problem than does the acceleration of nuclear particles. The mass of an electron is almost 2000 times smaller than that of a proton, and relativistic effects become important at a proportionately lower energy. This is why the conventional cyclotron is useless for electrons.

The first successful high energy accelerator for electrons was the betatron, built in 1941 by Kerst[10] at the University of Illinois. The betatron substitutes a continuous circumferential electric field for the cyclotron arrangement of a periodic electric field applied across a gap. This obviously avoids any difficulty of the ion's falling out of phase. The continuous circumferential field is achieved by the well-known principle of induction. The magnetic flux through the electron orbit varies with time, inducing the electric field along the orbit. Using the induction equation, $\int Eds=-(1/c)(\partial\phi/\partial t)$, where ϕ is the total flux through the orbit, it is easy to show that if the electron is to be held at a constant radius, r, during the acceleration, then the following relation between ϕ and the magnetic field H at the

[10] D. W. Kerst, *Physical Rev.* **60**, 47 (1941).

orbit must be satisfied:

$$\phi = 2\pi r^2 H. \qquad (5)$$

Thus, a large flux path must be provided if the electron is to reach a high energy. The total iron required is twice that for a synchrocyclotron, and it must be laminated to avoid eddy currents.

High energy betatrons are expensive, therefore, because of their iron requirement. There is also an upper limit to the energy which they can achieve, due to an effect which is completely negligible for nuclear particles. This is the radiation emitted by an accelerating charge. In a circular orbit, this is proportional to the fourth power of the ratio of the total energy of a particle to its rest energy. It is estimated that the radiation loss will prevent the betatron from ever going above about 400 Mev.

With the discovery of the principle of phase stability, it became possible to apply to electrons as well as nucleons the cyclotron technique of an external periodic electric field. This allows the radiation loss to be compensated up to a considerably higher energy than in the betatron. The limit is set in this case by the maximum gap voltage which can be achieved. The limit is not really known, but electron energies of one or two Bev are conceivable.

Another advantage possessed by the synchrotron over the betatron is of more immediate importance. There is no need, with the external electric field, to have a tremendous flux through the center of the orbit. The consequent saving in iron probably cuts down the over-all cost by a factor of three. This was the primary consideration which led, in 1945, to the planning of a 300-Mev electron synchrotron at Berkeley. It was built under the supervision of E. M. McMillan, one of the inventors, and first operated at full energy on January 17, 1949.[11]

General Description of the Synchrotron.—The only basic differences between the synchrotron and the synchrocyclotron are that the former accelerates electrons rather than nuclear particles and that modulation of the magnetic field rather than the frequency is employed. Because of its small rest mass, the total energy E of an electron is practically equal to its kinetic energy if the latter is more than a few Mev. This requires changing either H or ω by a factor of several hundred in reaching the hundred Mev range, [Eq. (5)], and the former task seemed easier. In addition, if ω is held constant, the radius of the electron orbit is also very nearly constant during the entire acceleration. This can be seen from the relation, $r = v/\omega$, connecting the angular and linear velocities. Except at the very beginning of the cycle, therefore, the orbital radius is close to the value c/ω since the electron velocity is almost that of light. The radius of the Berkeley machine was chosen to be one meter, corresponding to a frequency of 47.7 megacycles/sec.

It is clearly necessary to restrict the orbit if the saving in iron mentioned above is to be achieved. How then is one to get past the starting region when the electron moves relatively slowly? Some supplementary means must be found to carry out the acceleration up to one or two Mev, at which point the synchrotron can take over. This is accomplished by operating the machine as a betatron in the low energy region. A few flux bars (laminated iron bars which carry flux through the center of the orbit) can satisfy the betatron condition [Eq. (5)] until the magnetic field at the orbit reaches a value of ~80 gauss. The flux bars saturate at this point, when the electrons have energy of 2 Mev, and play no further role. The r-f field is now turned on, catching half or more of the circulating electrons in stable orbits, and these are carried up to the peak magnetic field of 10,000 gauss by synchrotron operation.

In Fig. 11 the entire magnetic field cycle is

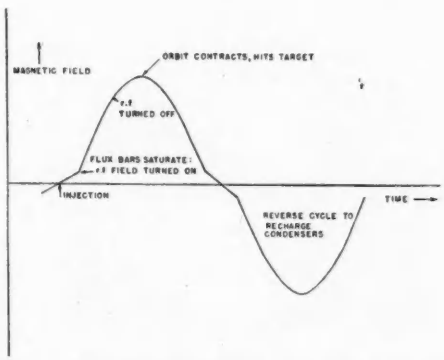


FIG. 11. The magnetic field in the synchrotron. The relative duration of some parts of the cycle are exaggerated so that they may be clearly visible.

[11] E. M. McMillan, *Physical Rev.* **75**, 1471(T) (1949).

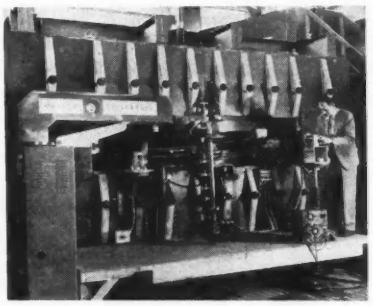


FIG. 12. Berkeley synchrotron. X-ray beam emerges at right from doughnut.

shown, with the various stages of electron acceleration indicated. No attempt has been made to get an external electron beam; the r-f is turned off just before the peak of the magnetic field is reached. The orbit then contracts and strikes a solid target projecting from the inner wall of the accelerating chamber. *Bremsstrahlung* results, giving a beam of photons whose energy ranges from 335 Mev down to zero. This x-ray beam penetrates the chamber walls almost unaffected and can be collimated with external absorbers. It might seem to be a less useful experimental tool than a beam of monochromatic 300-Mev electrons, but it can be shown that the properties of the two are almost identical.

The accelerating chamber is a hollow doughnut made of silica, with internal dimensions $2\frac{5}{8}$ inches vertically by $5\frac{3}{8}$ inches horizontally. The vacuum must be very high, 0.02 microns of mercury. One segment of the doughnut, occupying one-eighth of the circumference, is copper plated except for a $\frac{3}{8}$-inch transverse gap at one end. This segment forms a resonant cavity in which the accelerating r-f electric field is produced. The maximum gap voltage is 2.5 kev, while the average gain per turn is about 0.7 kev.

The excitation of the magnet presents quite a different problem from that in a cyclotron, where the magnetic field is constant. Here the magnet is the inductance of a huge oscillating circuit. An 805-microfarad capacitance, which requires a bank of 3328 individual condenser units, makes up the other half. The natural frequency of this circuit is 30 cycle/sec but it is triggered only six times a second by an electronic switch. In each pulse the switch is closed just long enough to allow one complete cycle.

Injection and Stability of the Synchrotron Beam.—The original injection into the doughnut presents the same problem as in an ordinary betatron. It has never been well understood, the chief difficulty arising from ions striking the back of the injector on one of their first few turns. The capture efficiency of the Berkeley machine is still lower than one might hope for, and work is continuing on this point. It was expected theoretically[6] that after the original injection the electrons would be easily caught in phase stable orbits at 2 Mev. This is indeed the case, more than half the beam making the transition. The stability of free oscillations in both betatron and synchrotron orbits depends on the same requirement as in the synchrocyclotron. The magnetic field intensity must decrease in the radial direction. Accordingly, the pole faces above and below the doughnut are shaped so that $(d \ln H/d \ln r) = -\frac{2}{3}$, a choice which seems to work well.

Synchrotron Performance.—The largest beams so far obtained have had 6×10^8 electrons per pulse, producing an x-ray intensity at one meter of 2300 roentgens per hour. In the first six months of operation for research, the machine was unavailable for a total of five weeks, due to breakdowns and continuing efforts to improve the beam. These interruptions should be progressively less frequent. Under normal conditions, the beam is available 90 percent of the time. (See Fig. 12.)

Shielding Problems at Berkeley.—A considerable number of fast neutrons are necessarily produced in both the cyclotron and linear accelerator wherever the ion beams strike solid matter. For reasons of safety, concrete shielding has been set up to prevent these neutrons from diffusing into areas where people must work. No such precautions need be taken with the synchrotron, which does not produce neutrons in abundance, although standing directly in the x-ray beam is to be avoided.

The cyclotron shielding consists of a concrete enclosure, with ten-foot thick walls and a four-foot thick roof, which surrounds the entire machine (see Fig. 13). In the direction in which neutrons are deliberately produced by allowing the proton or deuteron beam to fall on a solid

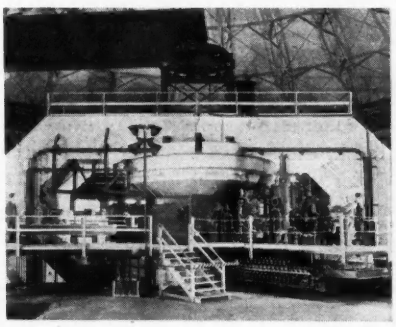
target, an additional large concrete block with collimating facilities is set up. Under normal operating conditions the energy delivered by fast neutrons outside the shielding is between 50 and 500 Mev per cm^2 per sec. Since the safe limit is supposed to be about 200 Mev and since a further increase in beam intensity is contemplated, another five feet of concrete is to be added to the side walls.

The linear accelerator produces less penetrating neutrons than the cyclotron, and to the present time only the area immediately surrounding the external target has been enclosed. The walls of this enclosure are only about one foot thick and there is no roof. Actually a considerable number of neutrons are produced by protons striking the drift tubes inside the tank and eventually these will have to be restricted by some kind of cover shield.

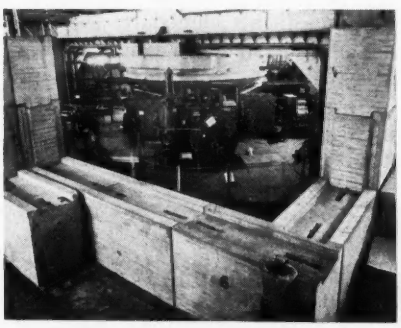
Summary and Discussion of Research Facilities at Berkeley

The research problems which can be investigated with the three operating high energy accelerators at Berkeley can be, somewhat arbitrarily, divided into three categories. The first is the study of nuclear reactions induced by high energy projectiles. The synchrocyclotron is the most versatile tool in this field, being able to supply internal beams of protons, deuterons, or alphas for bombardments at any energy up to the maximum values listed above. It can produce weaker external beams at the maximum energy. Neutrons of mean energy 90 Mev or 280 Mev can also be produced in the 184-inch cyclotron, as explained in the next paragraph. The linear accelerator gives protons only, and at a lower energy, but they are available in an intense, well collimated, monoenergetic external beam. Photonuclear reactions can be studied with the gamma-rays from the synchrotron. The intensity is low, but with newly developed techniques, not much is needed. High energy nuclear reactions will be the subject of the next article in this series.

A second field of interest is the interaction between fundamental particles. Leaving out mesons, the four fundamental particles available at Berkeley for experiment are protons, neutrons, photons, and electrons. High energy neutrons are most conveniently produced by stripping 190-Mev deuterons in the 184-inch cyclotron. The deuteron is a rather loose combination of neutron and proton, and the proton can be stripped away in a nuclear collision allowing the neutron to continue on with about half the energy of the initial deuteron. This stripping process is itself an interesting nuclear reaction and will be discussed in the next article. Neutrons with mean energy at about 280 Mev are projected forward from nuclei bombarded with the 350-Mev protons. This process will also be discussed. Fast electrons could be obtained indirectly by causing the gamma-rays from the synchrotron to produce positron-electron pairs. There is rarely any advantage in this because the most important interaction of an electron with other particles is via the electromagnetic field. The quanta of the electromagnetic field are, of course, photons, so one may just as well use them directly. The fundamental interactions are usually investigated



(a)



(b)

FIG. 13. (a) Berkeley synchrocyclotron without shielding. (b) View of Berkeley synchrocyclotron with shielding partially in place. Each concrete block is five feet thick.

with appropriate scattering experiments, e.g., neutrons scattered by protons, protons by protons, photons by electrons, and so on. Logically these are just the simplest types of reactions and should be discussed first. In practice, however, they are treated in a quite different and more rigorous way than other reactions and, therefore, will be deferred to the third article of the series.

The fourth article will be concerned with mesons, and again the separation is not completely logical. Mesons are believed to be responsible for nuclear forces and occur in many high energy reactions. However, artificially produced mesons are a new phenomenon and of great current interest. In addition, the connection with nuclear forces is not yet understood, and any discussion at this time must be on a semi-empirical basis. Enough information has accumulated, however, to make a separate article worthwhile.

The work described in this paper was performed under the auspices of the AEC.

Interaction between Magnetized Spheroids in Permeable Fluid Media

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ELDRIDGE[1] has discussed the forces between magnets immersed in permeable fluids, and has pointed out the misconceptions of magnetostatic theory which often occur.

In the present paper we derive, for the first time, the expression of the torque upon a uniformly magnetized spheroid of magnetic moment **M** in the field of a second spheroidal magnet **M′** for the Gauss "A" position.[2] We take the uniform intensity of magnetization of each magnet parallel to its axis. The magnets are immersed in a homogeneous and isotropic permeable fluid of great extent, and are widely spaced compared to the size of either. The spheroidal form is chosen for analytical simplicity and for its generality. In the limits our expression will accommodate the needle-like magnet and the circular magnetic shell.

While the solution of the problem in itself is but an exercise in potential theory, the result for the torque on M

$$|\mathbf{L}| = \frac{\mu}{\gamma\gamma'} \frac{2M'M}{R^3} \qquad (1)$$

is concise and interesting. Here μ is the permeability and γ represents an expression containing μ and the eccentricity of the spheroid. The significance of γ will be clear at the end of the development.

The purpose of the present paper is twofold: To show by a detailed and exact analysis that the permeability of a fluid medium does not have any single, general effect upon the forces between magnets, but that the effect depends qualitatively upon the geometrical distribution of magnetic charge; and to provide a quick reference for computing actual torques in specific cases.

Inserting the proper values of γ in each of the following instances, we get for the torque in the case of two needle-like magnets the familiar

$$|\mathbf{L}| = (2M'M)/(\mu R^3),$$

and for two circular magnetic shells

$$|\mathbf{L}| = (2M'M)/(R^3)\mu,$$

as pointed out by Eldridge;[1] while for one needle magnet and one circular shell

$$|\mathbf{L}| = (2M'M)/(R^3)$$

which is independent of μ. It is clearly erroneous to think, as is sometimes implied, that the forces between magnets are reduced in a permeable fluid by the presence of μ in the denominator.

The expression for the torque on any portion of a homogeneous fluid is derived and discussed

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[1] J. A. Eldridge, *Am. J. Physics* **16**, 327 (1948).

[2] The center of the first magnet M lies on the extended axis of the second magnet M' with its own axis at right angles thereto. Here and below primed quantities refer to the magnet M'.

by Page and Adams.[3] In a static magnetic field this relation becomes

$$\mathbf{L}=\int_\sigma \mathbf{r}\times\mathbf{HB}\cdot d\sigma-\frac{1}{2}\int_\sigma \mathbf{H}\cdot\mathbf{Br}\times d\sigma. \qquad (2)$$

We obtain Eq. (1) upon performing the integration on the right-hand side of Eq. (2) over the surface of the magnet M, taking the origin of our coordinate system at the magnet's center. In order to get **B** and **H** as functions of the coordinates, we first find the magnetic potential V. Since $\nabla\cdot\nabla V=0$, we have V when we find that solution of Laplace's equation which satisfies our boundary conditions.

We are to proceed then as follows: From the general solution of Laplace's equation we deduce the particular one which suits our boundary conditions. Then, taking the negative of its gradient yields **H**, and $\mathbf{B}=\mu\mathbf{H}$ outside the magnet. Putting these expressions for **B** and **H** into Eq. (2) and integrating gives our result as contained in Eq. (1).

Case I: Prolate Spheroid

Taking the origin of the coordinate system at the center of the magnet M, with the x axis along the axis of the spheroid in the sense of **M** and the y axis in the direction of **M′**, the two families of confocal orthogonal conicoids required for coordinate surfaces are the hyperboloids of two sheets

$$\frac{x^2}{c^2\xi^2}-\frac{\rho^2}{c^2(1-\xi^2)}=1,$$

and the prolate spheroids

$$\frac{x^2}{c^2\eta^2}+\frac{\rho^2}{c^2(\eta^2-1)}=1, \quad [\rho^2=y^2+z^2].$$

Then

$$x=c\xi\eta, \quad \text{and} \quad \rho=c[(1-\xi^2)(\eta^2-1)]^{\frac{1}{2}}.$$

The metrical coefficients are

$$a_\xi=c\left(\frac{\eta^2-\xi^2}{1-\xi^2}\right)^{\frac{1}{2}}, \quad a_\eta=c\left(\frac{\eta^2-\xi^2}{\eta^2-1}\right)^{\frac{1}{2}},$$

$$a_\phi=c[(1-\xi^2)^{\frac{1}{2}}(\eta^2-1)]^{\frac{1}{2}}.$$

[3] L. Page and N. I. Adams, *Electrodynamics* (D. Van Nostrand Company, Inc., New York, 1940), p. 292.

The third set of coordinate surfaces is a family of planes through the x axis, the azimuth angle ϕ being measured from the xy plane in the usual sense.

The general solution of Laplace's equation in spheroidal coordinates is

$$V=\sum_m\sum_n [AP_n^m(\xi)+BQ_n^m(\xi)][A'P_n^m(\eta)+B'Q_n^m(\eta)][C\cos m\phi+D\sin m\phi]. \qquad (3)$$

The boundary conditions at the surface $\eta=\eta_0$ of the magnet M are that the tangential component of the magnetic intensity **H** be continuous and the normal component of the magnetic induction **B** be continuous as we pass across the surface into the permeable medium.

Using the superscripts 0 and i to indicate quantities outside and inside the magnet respectively, the first boundary condition is

$$V^0=V^i, \quad \eta=\eta_0. \qquad (4)$$

If we express the constant intensity of magnetization **I** in the interior of the magnet in terms of a potential by the identity $\mathbf{I}=\nabla(Ix)$, the second boundary condition becomes

$$-\mu\frac{\partial V^0}{\partial\eta}=-\frac{\partial V^i}{\partial\eta}+4\pi I\frac{\partial x}{\partial\eta}, \quad \eta=\eta_0. \qquad (5)$$

Finally, our stipulation of large separation makes the field $\mathbf{H}_0'$ at M, due to M', constant over the space filled by M. This imposes upon us the final boundary condition that **H** must become equal to $\mathbf{H}_0'$ as we recede from M. That is,

$$V^0=H_0'y, \quad \eta\to\infty. \qquad (6)$$

The solutions satisfying these boundary conditions are: for the magnetic potential outside the magnet

$$V^0=[AP_1^1(\xi)P_1^1(\eta)+BP_1^1(\eta)Q_1^1(\eta)]\cos\phi+DP_1(\xi)Q_1(\eta),$$

and for the magnetic potential inside the magnet

$$V^i=EP_1^1(\xi)P_1^1(\eta)\cos\phi+GP_1(\xi)P_1(\eta),$$

where A, B, D, E, and G are constants.

Putting in the Legendre and associated

Legendre functions,

$$V^0=\left[A+B\left(\frac{1}{2}\log\frac{\eta+1}{\eta-1}-\frac{\eta}{\eta^2-1}\right)\right]\times[(\eta^2-1)(1-\xi^2)]^{\frac{1}{2}}\cos\phi+D\xi\left[\frac{1}{2}\eta\log\frac{\eta+1}{\eta-1}-1\right], \quad (7)$$

and

$$V^i=E[(\eta^2-1)(1-\xi^2)]^{\frac{1}{2}}\cos\phi+G\xi\eta. \quad (8)$$

From Eqs. (6) and (7) we get

$$A=H_0'c. \quad (9)$$

From Eqs. (4), (7), and (8), equating the coefficients of $\cos\phi$, we get

$$E=H_0'c+Bq, \quad (10)$$

where

$$q=\frac{1}{2}\log\frac{\eta_0+1}{\eta_0-1}-\frac{\eta_0}{\eta_0-1},$$

and

$$G=Dp, \quad (11)$$

where

$$p=\frac{1}{2}\log\frac{\eta_0+1}{\eta_0-1}-\frac{1}{\eta_0}.$$

Equations (2), (4) and (5) yield

$$B=\frac{(1-\mu)H_0'c}{(1-\mu)q-2\mu/[\eta_0(\eta_0^2-1)]}, \quad (12)$$

$$D=\frac{4\pi cI}{p-\mu q}, \quad (13)$$

$$E=H_0'c\left\{1+\frac{(1-\mu)q}{(1-\mu)q-2\mu/[\eta_0(\eta_0^2-1)]}\right\}, \quad (14)$$

$$G=4\pi cI(p/p-\mu q). \quad (15)$$

In order to evaluate the integral in Eq. (2), the position vector $\mathbf{r}$ and the surface element $d\boldsymbol{\sigma}$ must be expressed in spheroidal coordinates. The correct relations are:

$$d\boldsymbol{\sigma}=\mathbf{n}_1c^2[(\eta_0^2-\xi^2)(\eta_0^2-1)]^{\frac{1}{2}}d\xi d\phi,$$

and

$$\mathbf{r}=\mathbf{n}_1c\eta_0\left[\frac{\eta_0^2-1}{\eta_0^2-\xi^2}\right]^{\frac{1}{2}}+\boldsymbol{\xi}_1c\xi\left[\frac{1-\xi^2}{\eta_0^2-\xi^2}\right]^{\frac{1}{2}},$$

where $\boldsymbol{\xi}_1$ and $\mathbf{n}_1$ are unit vectors in the directions of increasing ξ and η, respectively.

As considerations of symmetry show the resultant torque to be about the z axis, we need evaluate only that component of $\mathbf{L}$. When evaluated, the integral in Eq. (2) becomes

$$|\mathbf{L}|=\mu\left(MH_0'\Big/\eta_0(\eta_0^2-1)(1-\mu)\times\left[\frac{1}{2}\log\frac{\eta_0+1}{\eta_0-1}-\frac{\eta_0}{\eta_0^2-1}\right]+1\right),$$

where the magnetic moment of the magnet is

$$M=4/3\pi c^3\eta_0(\eta_0^2-1)4\pi I.$$

Case II: Oblate Spheroid

For this case the required conicoids are the hyperboloids of one sheet

$$-\frac{x^2}{k^2\xi^2}+\frac{\rho^2}{k^2(1-\xi^2)}=1,$$

and the oblate spheroids

$$\frac{x^2}{k^2\zeta^2}+\frac{\rho^2}{k^2(\zeta+1)}=1.$$

These may be obtained from the equations for the prolate spheroidal coordinates by the substitutions $c=ik$ and $\eta=-ic\zeta$, where $i=(-1)^{\frac{1}{2}}$. The additional relations are $x=k\xi\zeta$ and $\rho=k[(1-\xi^2)(\zeta^2+1)]^{\frac{1}{2}}$. The analysis for this case is exactly similar to the previous one and yields

$$|\mathbf{L}|=\frac{\mu MH_0'}{1-(1-\mu)\zeta_0[(\zeta_0^2+1)\cot^{-1}\zeta_0-\zeta_0]}.$$

Page [4] has investigated the magnetic field of the uniformly magnetized spheroid. For large distances from the magnet, the potential is

$$V'=\frac{M'\cos\theta'}{\gamma'(x'^2+\rho'^2)}.$$

Relative to the axes attached to M', the magnet M is located at $\theta'=0$, $x'=R$. Then

$$H_0'=-(\partial V'/\partial x')_{x'=R,\,\theta'=0}=2M'/\gamma'R^3.$$

[4] L. Page, *Physical Rev.* **44**, 112 (1933).

Collected Results

The ratio of the torque in vacuum to that in a permeable fluid is

$$\frac{L_1}{L_\mu}=1+(\mu-1)\eta_0^2\left[1-\frac{\eta_0^2-1}{2\eta_0}\log\frac{\eta_0+1}{\eta_0-1}\right]$$

for the prolate spheroid, and

$$\frac{L_1}{L_\mu}=1+(\mu-1)\zeta_0^2\left[\frac{\zeta_0^2+1}{\zeta_0}\cot^{-1}\zeta_0-1\right]$$

for the oblate spheroid. These ratios are, in each case, just the ratios H_1/H_μ of the magnetic intensity external to a uniformly magnetized spheroid in vacuum to the corresponding magnetic intensity in a permeable medium to which Page has assigned the symbol γ. The expression of L can now be written in its final form

$$|\mathbf{L}|=\frac{\mu}{\gamma\gamma'}\frac{2M'M}{R^3}. \qquad (1)$$

Page has represented γ graphically in terms of quantity

$$r=\frac{\gamma-1}{\mu-1}=\eta_0^2\left[1-\frac{\eta_0^2-1}{2\eta_0}\log\frac{\eta_0+1}{\eta_0-1}\right]$$

for the prolate case, and

$$r=\zeta_0^2\left[\frac{\zeta_0^2+1}{\zeta_0}\cot^{-1}\zeta_0-1\right]$$

for the oblate case.

In terms of the eccentricity $\epsilon=1/\eta_0$ of a prolate spheroid, and $\epsilon=1/(\zeta_0^2+1)$ of an oblate one,

$$r=\frac{1}{\epsilon^2}\left[1-\frac{1-\epsilon^2}{2\epsilon}\log\frac{1+\epsilon}{1-\epsilon}\right]$$

for the former, and

$$r=\frac{1}{\epsilon^2}\left[\frac{(1-\epsilon^2)^{\frac{1}{2}}}{\epsilon}\cot^{-1}\frac{(1-\epsilon^2)^{\frac{1}{2}}}{\epsilon}-(1-\epsilon^2)\right]$$

for the latter.

Values of r for several values of ϵ are tabulated and represented graphically by Page. In order to make use of our result, the values of γ and γ' are calculated from the values of r corresponding to the eccentricity of M and to that of M'.

To find the torque in the example of two needle-like magnets (prolate spheroids of eccentricity $\epsilon=1$), we refer to Page and find $r=r'=1$, then $\gamma=\gamma'=\mu$ and

$$|\mathbf{L}|=(2M'M)/(\mu R^3).$$

Similarly in the example of two circular magnetic shells (oblate spheroids of eccentricity $\epsilon=1$) we find referring to Page that $r=r'=0$, therefore $\gamma=\gamma'=1$, and

$$|\mathbf{L}|=(2M'M)/(R^3)\mu.$$

For the case of a pair of spherical magnets, $\epsilon=\epsilon'=0$, we find $r=r'=\frac{2}{5}$, hence $\gamma=\gamma'=(2\mu+1)/3$ and

$$|\mathbf{L}|=\frac{9\mu}{(2\mu+1)^2}\frac{2MM'}{R^3},$$

which is Page's[5] result.

The present work was suggested by Professor Leigh Page and is rightly an extension of reference 4, its prototype.

[5] L. Page, *Introduction to theoretical physics* (D. Van Nostrand Company, Inc., Second Ed., 1935), p. 44.

A mathematical investigation always obeys the law of the conservation of knowledge; we never get out more from it than we put in. The knowledge may be changed in form, it may be clearer and more exactly stated, but the total amount of the knowledge of nature given out by the investigation is the same as we started with.—HENRY A. ROWLAND

The Prediction of Achievement in Sophomore Engineering Physics at the University of Minnesota*

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1. The Problem

THE elementary physics course is generally considered to be a most important foundation course for college students majoring in one of the pure or applied physical sciences. A year's experience (1946–47) with large lecture sections convinced the instructors of the course sequence in general physics at the University of Minnesota that the lecture method of instruction did not adequately meet the scholastic needs of the superior students. An exploratory study was proposed, therefore, to investigate the prognostic value of various factors with respect to achievement in college physics.

A research project was initiated by the Physics Department with the cooperation and assistance of the University's Bureau of Institutional Research. Primary emphasis in the project was placed on the following question: *Can achievement in the sophomore engineering physics course sequence be predicted from information available in the student's record?* It was hoped that a satisfactory answer to this question would yield criteria which might be useful in selecting students for an accelerated section in physics. An experimental group selected on the basis of these criteria would enable the instructor to develop the subject matter from a more advanced point of view. Limited enrollment would also provide greater opportunity for individual attention through more frequent teacher-student contacts.

2. Sophomore Engineering Physics at the University of Minnesota

Students majoring in physics, chemistry, or mathematics in the College of Science, Literature and the Arts, and practically all students in the Institute of Technology are required to take three quarters of general physics (Physics 7, 8, 9), usually in the sophomore year. The minimum mathematics prerequisite for the course is concurrent registration in differential calculus. Physics 7 deals with the subject of Mechanics, Physics 8 with Heat and Electricity, and Physics 9 with Sound, Light and Modern Physics. The students consider the physics sequence, and perhaps rightly so, as one of the "high hurdles" of their undergraduate program.

The instructional procedure in the general physics course sequence at the University of Minnesota differs somewhat from the sequence taught in other schools in that there are no formal quiz sections. Four lectures per week are scheduled, with voluntary attendance on the part of the students. A full-period written test is given once a week. These weekly tests, accounting for 50 to 60 percent of the final grade, are scored by well-qualified junior and senior students under the supervision of a staff member in charge of the course. Several conference hours are scheduled every week for students in need of individual assistance, with a graduate assistant in charge. Here, again, attendance is voluntary. The laboratory work is fairly conventional, except that written tests *and* examinations involving apparatus are given at the end of each quarter to yield a composite laboratory grade which constitutes 20 percent of the final grade. The final three-hour examination counts 20 to 30 percent of the final mark. A composite of these numerical scores is translated into letter grades A, B, C, D, and F at the end of each quarter's course.

During the year for which the study was conducted, 1946–47, the second edition of Hausmann and Slack's *Physics* was used as a textbook. The majority of the students for that year were male veterans enrolled in the Institute of Technology.

3. The Method of Prediction

The records of students enrolled in the general physics course sequence at the University of Minnesota during 1946–47 furnished the basic data for the study. Official transcripts and other University records were analyzed to select pos-

* This study was supported and sponsored by the Committee on Institutional Research, University of Minnesota, through the University Bureau of Institutional Research.

sible measures which could be used as predictors of physics achievement. Test scores and final grades of individual students in the three-quarter physics sequence provided the evidence of achievement. The problem resolved itself into that of matching these two sets of information in such a way that the most effective predictors of physics achievement could be identified. As such, the problem became a statistical one in which the multiple regression equation was set up to predict grades of individual students in the physics sequence. This equation could then be applied as one device to be used in screening students for admission to the special section in engineering physics.

In a statistical problem of this kind the two sets of measures just described are referred to as *dependent* and *independent* variables. Independent variables in this instance were those measures which were used to predict achievement in the physics course sequence. The dependent variables were the measures of achievement in that course sequence.

The specific *dependent* or criterion variables used in this study were:

(1) Final grades for three quarters in the physics course sequence. The letter grade for each quarter was quantified by assigning a value of 4 points to A, 3 points to B, 2 points to C, 1 point to D, and 0 to F.

(2) Raw score on the Cooperative Physics Test for College Students, Forms E and F. In Physics 7, the Cooperative Test score constituted 15 percent of the final grade; in Physics 8, 9 percent; in Physics 9, 21 percent (Light, 10.5 percent; Sound 4.8 percent; Modern Physics, 5.7 percent).

In like manner, the six *independent* variables obtained from the student's permanent record were as follows:

(1) High school percentile rank (HSR), translated into T-scores.
(2) Raw score on the American Council on Education Psychological Examination (ACE).
(3) Raw score on the Cooperative English Test, Form OM (Coop. Eng.).
(4) Honor point ratio in the Institute of Technology mathematics courses in the freshman year (HPR Math.). The honor point ratio is defined as the total number of honor points divided by the total number of credits earned and failed.
(5) Honor point ratio in the Institute of Technology chemistry courses in the freshman year (HPR Chem.).
(6) Total honor point ratio in all Institute of Technology courses taken in the freshman year (HPR Fresh.).

4. The Sample Population

In spite of the fact that the students in the general physics course sequence constitute a fairly select group, the investigation was restricted to a more homogeneous sample. The criteria listed below were set up to select a sample of students who were representative of the Institute of Technology sophomores taking Physics 7, 8, 9 at the University of Minnesota.

The investigation started with an original population of 704 students who were enrolled in Physics 7 during the fall quarter, 1946. A student's record was eliminated from the sample if it failed to satisfy one or more of the following conditions:

(1) Registration as a regular student in the Institute of Technology at the University of Minnesota. (Note: Many of the 704 students were registered in other colleges of the University.)
(2) A minimum of 24 credit hours earned in residence as a freshman in the Institute of Technology.
(3) A minimum of 15 credit hours in mathematics earned in the Institute of Technology.
(4) A minimum of 13 credit hours in chemistry earned in the Institute of Technology.
(5) A home address somewhere in the continental U. S. A.
(6) Original enrollment in the general physics course sequence in the fall quarter of 1946.
(7) Male.

Criterion 1 excluded students from other colleges, including adult specials. Criteria 2, 3, and 4

TABLE I. Means, standard deviations, and zero-order correlation coefficients for all samples in Physics 7, 8, 9, University of Minnesota, 1946–47.

Variables	Sample*	Mean	S.D.	Correlation coefficients												
				X_2	X_3	X_4	X_5	X_6	Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Z_4	Z_5
X_1, High School Percentile Rank (HSR)	I	57.6	7.94	0.39	0.40	0.29	0.30	0.35	0.24	0.22	0.17	0.18	0.20	−0.01	0.15	0.05
	II	57.4	8.13	0.37	0.40	0.31	0.33	0.38	0.25	0.27		0.14	0.16			
	III	57.1	8.23	0.40	0.40	0.46	0.66	0.42	0.32			0.21				
X_2, American Council on Education Psychological Examination	I	88.6	23.48		0.68	0.22	0.17	0.26	0.23	0.25	0.24	0.24	0.26	0.37	0.35	0.31
	II	88.2	23.56		0.67	0.23	0.20	0.29	0.24	0.28		0.23	0.29			
	III	87.9	23.14		0.68	0.29	0.22	0.32	0.35			0.27				
X_3, Coop. English (Eng.)	I	172.0	42.08			0.13	0.17	0.23	0.20	0.23	0.14	0.21	0.32	0.31	0.29	0.25
	II	172.0	41.68			0.15	0.17	0.24	0.19	0.23		0.18	0.31			
	III	172.1	41.77			0.18	0.19	0.25	0.21			0.18				
X_4, Freshman Mathematics Honor Point Ratio (Math.)	I	1.6	0.79				0.65	0.88	0.60	0.53	0.51	0.28	0.24	0.29	0.32	0.23
	II	1.6	0.79				0.67	0.89	0.59	0.58		0.26	0.26			
	III	1.4	0.84				0.68	0.90	0.66			0.38				
X_5, Freshman Chemistry Honor Point Ratio (Chem.)	I	1.6	0.74					0.86	0.49	0.46	0.39	0.21	0.27	0.15	0.28	0.23
	II	1.6	0.75					0.87	0.49	0.49		0.19	0.29			
	III	1.4	0.78					0.86	0.53			0.32				
X_6, Freshman Total Honor Point Ratio (HPR)	I	1.6	0.60						0.65	0.59	0.57	0.28	0.32	0.29	0.34	0.29
	II	1.5	0.60						0.64	0.60		0.26	0.26			
	III	1.5	0.64						0.70			0.40				
Y_1, Final Grade in Physics 7	I	2.0	0.83							0.65	0.56	0.53	0.40	0.37	0.41	0.30
	II	2.0	0.82							0.64		0.52	0.40			
	III	1.7	1.03									0.63				
Y_2, Final Grade in Physics 8	I	2.0	0.92								0.62		0.60	0.34	0.40	0.44
	II	1.9	0.97										0.59			
Y_3, Final Grade in Physics 9	I	2.2	0.85										0.40	0.58	0.40	0.52
Z_1, Coop. Mechanics (Raw Score×3)	I	74.2	20.76										0.41	0.38	0.34	0.36
	II	73.8	20.57										0.40			
	III	70.6	22.48													
Z_2, Coop. Electricity (Raw Score×2)	I	65.9	19.80											0.36	0.38	0.42
	II	64.8	20.19													
Z_3, Coop. Light (Raw Score×3)	I	53.0	15.08												0.45	0.90
Z_4, Coop. Sound (Raw Score×3)	I	29.6	8.75													0.37
Z_5, Coop. Modern Physics (Raw Score×3)	I	24.1	10.07													

* Group I —175 students who completed Physics 7, 8, and 9.
Group II —191 students who completed Physics 7 and 8 only.
Group III—239 students who completed Physics 7 only.
Note: Samples I, II, and III are not independent.

insured the usual subject-matter background in chemistry and mathematics and excluded transfer students. Criterion 5 eliminated the foreign students who might have had language and background handicaps. The sixth criterion excluded students repeating the course and seventh excluded the relatively few women who take this sequence of courses.

Of the 704 students who were registered in Physics 7 during fall quarter, 1946, approximately half of them (343) satisfied all of the above criteria and earned a grade in Physics 7. This group constituted the total sample of engineering students who took the normal pattern of courses in the Institute of Technology. Many of the records of these students, however, lacked some of the information which had been previously listed under independent variables. In fact, complete information on the six independent variables was available for 239 of the 343 students in this group.

Logically the sample that furnished the most information appeared to be the reasonable one to use. Some evidence was necessary, however, to support the thesis that this smaller group could be considered as representative of the total sample. Such evidence was obtained by calculating *t*-tests of significance for differences between means secured from the sample with complete information and the balance of the total sample. Variances of these two groups were tested in like manner using the *F*-ratio. In both instances the groups could be compared only on those variables which were common to the two

samples. These included final grades in Physics 7, honor point ratios in chemistry and mathematics, and total honor point ratio for the freshman year. Since none of these tests of significance yielded F or t ratios (the statistical tests employed) significant at the 5 percent level, the two samples were believed to be homogeneous. Final analyses were therefore based upon students for whom test and achievement records in Physics 7 were complete —the basic sample of 239 students as noted above.

For convenience in analysis, this basic sample was subdivided into three parts corresponding to students who received grades in Physics 7, 8, and 9. As might be expected, these three groups overlap in membership. They have been identified as follows:

Group I—175 students, who completed with a final grade the entire sequence, Physics 7, 8, and 9,

Group II—191 students, who completed Physics 7 and 8 only, and

Group III—the 239 students, in the sample who completed only Physics 7 to the point of receiving a final grade.

Results and conclusions are based on the findings for these three groups of students.

5. Zero-Order Correlations

In order to establish the predictive value of each independent variable, zero-order correlation coefficients (r) were determined. The coefficients, as well as the means and standard deviations for all samples, are shown in Table I. Inspection of this table shows that:

(1) The best single predictor of the final grade in Physics 7 for all groups is the total honor point ratio for the freshman year. ($r_{\mathrm{I}}=0.65$; $r_{\mathrm{II}}=0.64$; $r_{\mathrm{III}}=0.70$).

(2) The best single predictor of the final grade in Physics 8 for Groups I and II is the final grade in Physics 7. ($r_{\mathrm{I}}=0.65$; $r_{\mathrm{II}}=0.64$). The second best predictor is the total freshman honor point ratio ($r_{\mathrm{I}}=0.59$; $r_{\mathrm{II}}=0.60$).

(3) The best single predictor of the final grade in Physics 9 is the final grade in Physics 8 ($r_{\mathrm{I}}=0.62$). The next best predictor is the total freshman honor point ratio ($r_{\mathrm{I}}=0.57$).

(4) The correlations between scores on various Cooperative physics tests and the independent variables are, with one exception, positive but low. The highest coefficient is obtained between the Cooperative Mechanics Test and the total freshman honor point ratio ($r=0.40$). One possible explanation is that this test is measuring something different from the other measures used in computing final grades. Moreover, the students were accustomed to the typical problem-derivation-definition type of examinations during the quarter rather than the multiple-choice type used in the Cooperative tests.

(5) The high correlations between the total honor point ratio and chemistry ($r=0.86$ to 0.87) are readily attributable to (a) The presence of self-correlation and (b) the further correlations (0.65 to 0.68) between chemistry and mathematics. Both mathematics and chemistry grades constitute a major fraction of the student's work in the freshman year.

6. Multiple Correlations

The predictive values of several combinations of independent variables were investigated by calculating coefficients of multiple correlation (R). Little difference appeared between zero-order correlations and the multiple correlations using High School Rank, ACE, and the total freshman honor point ratio. (See Table II.) Highest values for prediction of final grades in Physics 7, 8, and 9 were zero-order correlations of 0.70, 0.60, and 0.57 and multiple correlations of 0.71, 0.61, 0.58, respectively. Multiple correlations were unchanged (to two decimal places) by addition of scores on the Cooperative English test for the Physics 7 group. Moreover, the predictive efficiency of freshman honor point ratio was little improved by the addition of high school rank or ACE. Because honor point ratios in mathematics and chemistry were not independent of freshman honor point ratio, these two variables were substituted for the latter with no

TABLE II. Physics 7, 8, 9, University of Minnesota, 1946–47. Multiple correlation coefficients.

Predictive variables	Dependent variables: Physics 7 final grade III (Y_1)	Physics 8 final grade II (Y_2)	Physics 9 final grade I (Y_3)	Coop. mechanics III (Z_1)	Coop. electricity II (Z_2)	Coop. light I (Z_3)
ACE, Total HPR (X_2, X_6)	0.71	0.61	0.58	0.42	0.37	0.42
HSR, ACE, Total HPR (X_1, X_2, X_6)	0.71	0.61	0.58			
HSR, ACE, Eng., Math., Chem. (X_1, X_2, X_3, X_4, X_5)	0.70					
HSR, ACE, Math., Chem. (X_1, X_2, X_4, X_5)	0.70					

change in the resulting multiple correlation coefficients. However, the inclusion of mathematics and chemistry honor point ratios as separate variables utilized more information about students, and consequently could be used to improve the prediction equations.

7. The Multiple Regression Equation for Physics 7

Although the multiple correlation is no better for predicting a grade in Physics 7 than the zero-order correlation for the total freshman year honor point ratio, there are many problems in which a combination of several variables is likely to give higher predictive efficiency than a single variable. Consequently, the multiple regression equation as discussed below is merely *illustrative* of the possible application of this technique to grade prediction studies.

The multiple correlation coefficients for Physics 7 students were sufficiently high to warrant the derivation of a multiple regression equation or a predictive formula.[1] Although several combinations of independent variables might be employed, those used for *illustrative* purposes in the present instance are shown below in equation form:

$$Y' = \bar{Y} + b_1(X_1 - \bar{X}_1) + b_2(X_2 - \bar{X}_2) + b_4(X_4 - \bar{X}_4) + b_5(X_5 - \bar{X}_5),$$

where Y' = predicted final grade in Physics 7, $\bar{Y}$ = the mean final grade in Physics 7 for the Sample III, b_1, b_2, b_4, b_5 are the partial regression coefficients, X_1 = High School Percentile Rank, X_2 = Raw Score on ACE, X_4 = Mathematics Honor Point Ratio, X_5 = Chemistry Honor Point Ratio, and $\bar{X}_1$, $\bar{X}_2$, $\bar{X}_4$, $\bar{X}_5$ are the means of the respective independent variables for Sample III.

The final equation for the prediction of Physics 7 grades from original scores for these variables was shown to be

$$Y' = 0.6725 - 0.0916X_1 + 0.0094X_2 + 0.6300X_4 + 0.3123X_5.$$

For instance, a student whose high school rank is 49, whose ACE raw score is 92, whose mathematics honor point ratio is 1.67 and whose chemistry honor point ratio is 1.33, would have a predicted grade in Physics 7 of 0.98 (when A = 4, B = 3, C = 2, D = 1, F = 0).

Using the Johnson-Tsao formula,[2] the standard errors of the individual predicted scores ($S_{Y'}$) was computed for several students. Ninety-five percent fiducial limits were also calculated.

Fiducial limits (0.95) = $Y \pm 1.970(S_{Y'})$.

In the example cited above, the standard error was 0.086. The fiducial limits were 0.82–1.15, indicating a grade of D on the conversion table employed. In interpreting these findings, one may be confident that this statement will be correct 95 times out of 100, since the 95 percent fiducial limits were employed. It must be remembered, however, that the predicted grade, 0.98 in this case, is the mean grade of a large number of individuals having identical values for the independent variables. As a result, the grade predicted for a single student will sometimes fall outside the fiducial limits, depending upon the

[1] Palmer O. Johnson, *Statistical methods in research* (Prentice-Hall, New York, 1949), Chap. XIV.

[2] Johnson, *op. cit.*, pp. 342–43.

level of probability employed in setting these limits.

To compare the relative predictive values of the independent variables, they must be expressed in terms of their respective means and standard deviations rather than the raw scores used in the above illustration. The corresponding partial regression coefficients are called *standard* partial regression coefficients. In this case, the mathematics honor point ratio has the largest relative weight, for its standard partial regression coefficient of 0.5103 is more than twice as great as that of the next best predictors. (ACE = 0.2104 and HPR Chem. = 0.2374.) The high school rank has the smallest and a *negative* value (−0.1564). The latter fact seems somewhat contrary to most studies of this kind which show a positive and significant correlation between high school rank and achievement. A plausible explanation is that the group under investigation consisted mostly of veterans with a considerable age variation. In many cases a long period of time had elapsed between graduation from high school and enrollment in the physics course, thus reducing the effect of the high school ratings.

Similar comparisons could be made in this fashion for other combinations of predictive variables. This technique also provided a means of testing the significance of each standard partial regression coefficient and reduction in number of variables to those which have the most predictive value when used singly or in combination. Analysis of this kind, for example, showed that total honor point ratio during the freshman year with its zero-order correlation of 0.70 was, for practical purposes, as predictive of achievement in Physics 7 as the best combination of independent variables which yielded only 0.71.

8. Application of the Investigation Results

The findings of this study were used to select students for the special "honors" section in Physics 7, 8, 9 for fall, 1948. For practical reasons and because of the relatively small gain in predictive efficiency through use of several independent variables, only freshman honor point ratio was used in the original screening. This was supplemented by interviews to determine student interest in joining such a section. Professor J. H. Williams, the original sponsor of the special course idea was in charge of the section throughout 1948–49. His experiences with the group are summarized in the extract from a report to Dean T. R. McConnell, reproduced below.

> These students were selected on the basis of their excellent scholastic records in their freshman year and, in some cases, their sophomore year of work. In addition, I held a conference of about fifteen minutes with each student before he *volunteered* to enter the class and perform the additional work required. In this way I was assured of an interested group of approximately thirty students with a wide variety of major interests.
>
> Of the original 29 students enrolled in the fall quarter, 6 transferred out to the regular section during the fall term. Of the remaining 24 students, the grade distribution was 11 A's, 9 B's, 4 C's. The winter quarter enrollment was 24 students, 4 new students, 20 old students. Transferred during the winter quarter 1; grade distribution 11 A's, 8 B's, 4 C's. The spring quarter enrollment was 19; 0 new students, 19 old students. Transferred during spring quarter 0; grade distribution 13 A's, 4 B's, 2 C's.
>
> The trial method of instruction employed differed markedly from my usual practice with sections of hundreds of students in one room studying the same subject. Approximately one-third of the time was spent in discussing questions raised by the students. A selection of the most difficult or most fundamental material was made and treated at greater length and in more detail than is usual. The remaining material was assigned as independent work for the students. Most of the students who transferred did so because of the extra work required of them by this method of teaching. The stimulation of the discussions soon influenced most of the students, and the main difficulties encountered in the class procedure were to terminate the discussion or to answer the questions within the mathematical knowledge of the students.
>
> I am sure that I have profited materially by this experience. The deepest satisfaction that I have acquired comes from the feeling that some of these students have acquired a real sense of reasoning power and a confidence in their ability as prospective scientists.[3]

During the past summer, too, Dr. Williams has been interviewing candidates for a special section and will be its instructor during the current school year.

9. Extension of the Investigation

The results of the investigation should not be construed as definitive. It is hoped that similar studies can be initiated in other schools. Tentative plans are being made at the University of Minnesota to repeat the study for other classes which followed the group discussed above. Some

[3] Private communication to the authors.

changes may be expected, due to the moving on of the veteran group which constituted most of this sample. It is also hoped to make a follow-up study of the students in the special section to verify the validity of the selection techniques.

Other variables which might well be included in such investigation would involve motivational factors, interests, and attitudes of students. These were not available in the present inquiry.

10. Summary

(1) The investigation dealt with the prediction of student grades in the sophomore general physics courses at the Institute of Technology, University of Minnesota, in 1946–47.

(2) The achievement criteria were (a) the final grade, (b) the scores on the several Cooperative Physics Tests.

(3) The prediction variables were (a) the high school percentile rank (b) score on the American Council on Education Psychological Examination (c) score on the Cooperative English Tests (d) freshman mathematics honor point ratio (e) freshman chemistry honor point ratio, and (f) total freshman honor point ratio.

(4) Three homogeneous samples of engineering students were selected, consisting of (a) those who completed one quarter of physics, (b) those who completed two quarters of physics, and (c) those who completed three quarters of physics.

(5) As determined by this investigation, the best single predictor of final grade in the first quarter of physics is the total honor point ratio for the freshman year: $r=0.70$.

The use of additional independent variables by development of a multiple regression equation did not improve the predictive efficiency of this r.

(6) The best single predictor of the final grade in the second quarter of physics is the final grade for the first quarter: $r=0.65$.

(7) The best single predictor of the final grade in the third quarter is the final grade in physics for the second quarter: $r=0.62$.

(8) Achievement as measured by the Cooperative Physics Tests cannot be reliably predicted in terms of the independent variables employed in this sample because of the low correlations.

(9) Tests of significance indicate that high school percentile rank, the ACE examination, and the mathematics and chemistry honor point ratios contribute to the prediction of the final grade in first quarter physics.

(10) An illustrative regression equation was written to predict the final grade in the first quarter of physics from four independent variables. The largest relative contribution was made by the honor point ratio in freshman mathematics.

(11) The accuracy with which the final grade in the first quarter of physics can be predicted is measured by the multiple correlation coefficient: $R=0.71$. Considering the fact that the sample is highly selected, the value of the coefficient is relatively high for studies of this type.

(12) The findings of the investigation were useful in selecting engineering students for a special "honors" course in sophomore general physics.

(13) Plans are being made at the University of Minnesota to extend and refine this investigation for the physics classes that followed the group investigated. Similar studies in other schools would be highly desirable.

(14) The above conclusions should be interpreted as tentative, within the limitations of the sample and the variables used in this study.

Symposium on Molecular Structure and Spectroscopy

A Symposium on Molecular Structure and Spectroscopy will be held at the Mendenhall Laboratory of Physics at The Ohio State University from June 12 through June 17, 1950. There will be discussions of the interpretation of molecular spectroscopic data as well as methods of obtaining such data. In addition, there will be sessions devoted to those phases of spectroscopy of current interest. A dormitory will be available for those who wish to reside on the campus during the meeting. For further information, or for a copy of the program when it becomes available, write to Professor HARALD H. NIELSEN, Mendenhall Laboratory of Physics, The Ohio State University, Columbus 10, Ohio.

Derivation of Thermal Emittance Equation

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THE total thermal emittance of a test surface (ϵ_t) is sometimes computed from the equation

$$\epsilon_t = (T_b^4 - T_r^4)/(T_t^4 - T_r^4), \qquad (1)$$

where T_t is the absolute temperature of the test surface during measurement, T_r is the absolute temperature of the measuring thermopile and its surroundings, and T_b is the absolute temperature of a blackbody which, with the same geometry, produces the same thermopile indication as is produced by the test surface.

In recent work it became desirable to investigate the derivation of this equation, to consider the assumptions involved and the conditions under which the equation applied, and to determine the modifications of the equation which would be necessary if the thermopile receiving surface and the blackbody used for comparison did not have emittances which were truly unity. This study led to the following derivation.

Suppose that a test surface t, of which the thermal emittance ϵ_t is to be determined, is at some elevated absolute temperature T_t, and exchanges radiant energy through suitable apertures in screens with a thermopile receiving surface r, not necessarily a blackbody, at a temperature T_r which may be near room temperature. The apertures and enclosure of the thermopile are also at the temperature T_r. The energy per second leaving unit areas of the test surface and of the receiving surface consists of a radiated part E and a reflected part R. These two parts are indicated by E_t and R_t for the test surface, and by E_{rt} and R_{rt} for the receiving surface. The secondary subscript t on E_r and R_r indicates that the receiver is facing the test surface t.

Under the above conditions the thermopile of the receiving surface will develop an emf which is a measure of the difference in the two rates of exchange of energy. A comparison surface b, preferably a blackbody but not at present assumed to have an emittance of unity, is then substituted for the test surface, the geometry remaining the same, and by suitable adjustment of its temperature the same thermopile reading is obtained. Under these circumstances the rate at which excess energy is absorbed by the receiver is the same in the two cases, and this can be expressed

$$(E_t + R_t) - (E_{rt} + R_{rt}) = (E_b + R_b) - (E_{rb} + R_{rb}). \qquad (2)$$

The quantities E_{rt} and E_{rb} are equal since they represent the rate at which energy is emitted from unit area of the surface r at equal temperatures. The question of the equality of R_{rt} and R_{rb}, however, requires some consideration. It is possible that the energy coming to the receiving surface from two different surfaces might be so different in frequency distribution that the receiving surface would reflect a larger fraction of one than of the other even though the incident energy from each had the same total intensity. However, Worthing[1] has shown that the energy distribution curves for tungsten (with an emittance of 0.27) and for a blackbody at the same temperature have the same general form. A blackbody curve, for a lower temperature at which the total energy radiated per square centimeter per second would equal that of the tungsten, would still have the same form, but have the peak of its energy at a longer wavelength. There would be no marked difference in the two cases in the fraction of the radiation reflected by the receiver unless it were quite selective in the region of the two peaks. In practice, a receiver used for radiation measurements would have at least a moderate approach to blackbody conditions and so would probably not be appreciably selective in this region. Also, with this kind of a receiver, only a small fraction of the incident energy would be reflected at all, and so the selectivity would be a second-order effect. Consequently, it can be assumed in practice that $R_{rt} = R_{rb}$, leaving the equation

$$E_t + R_t = E_b + R_b. \qquad (3)$$

[1] A. G. Worthing, *Amer. Inst. of Mining and Met. Eng.*, 1920 Volume on Pyrometry, p. 370.

When the reflected energies R_t and R_b are evaluated, it is necessary to indicate that R_t and R_b are the fractions of the energy per unit area per second coming from the receiver and screen surfaces which are not absorbed at the surfaces t and b, respectively. These energies have the E_r and R_r components previously discussed. The relationships can be written

$$R_t=(E_r+R_r)(1-\epsilon_t) \tag{4}$$

and

$$R_b=(E_r+R_r)(1-\epsilon_b). \tag{5}$$

The additional equation

$$R_r=(E_b+R_b)(1-\epsilon_r) \tag{6}$$

can be written for the reverse relationship when energies are exchanged between surfaces r and b.

The last two equations can be solved simultaneously to give

$$R_b=\frac{E_r(1-\epsilon_b)+E_b(1-\epsilon_r)(1-\epsilon_b)}{1-(1-\epsilon_r)(1-\epsilon_b)} \tag{7}$$

and

$$R_r=\frac{E_b(1-\epsilon_r)+E_r(1-\epsilon_b)(1-\epsilon_r)}{1-(1-\epsilon_r)(1-\epsilon_b)}. \tag{8}$$

By using Eq. (4), R_t can be eliminated from Eq. (3) and then R_b and R_r can be eliminated by use of Eqs. (7) and (8). If, in addition, the various values of E are replaced by the appropriate $\epsilon\sigma T^4$, it is found that

$$\epsilon_t=\frac{\epsilon_b T_b^4-\epsilon_r T_r^4-\dfrac{\epsilon_b^2 T_b^4(1-\epsilon_r)-\epsilon_r^2 T_r^4(1-\epsilon_b)}{\epsilon_r+\epsilon_b-\epsilon_b\epsilon_r}}{T_t^4-\epsilon_r T_r^4-\dfrac{\epsilon_b(1-\epsilon_r)T_b^4+(1-\epsilon_r-\epsilon_b+\epsilon_b\epsilon_r)\epsilon_r T_r^4}{\epsilon_r+\epsilon_b-\epsilon_b\epsilon_r}}. \tag{9}$$

This equation should give correct values for ϵ_t from the measured temperatures, provided the values of ϵ_b and ϵ_r are known, even though they are not unity. There is possibly the additional requirement that ϵ_r shall have a value fairly near unity so that, as previously discussed, the possibility of error due to selective reflection is small.

If the emittance of the receiver is unity, i.e., if $\epsilon_r=1$, then

$$\epsilon_t=\frac{\epsilon_b(T_b^4-T_r^4)}{T_t^4-T_r^4}. \tag{10}$$

If, instead, the emittance of the comparison surface is unity, i.e., if $\epsilon_b=1$,

$$\epsilon_t=\frac{T_b^4-T_r^4}{T_t^4-T_r^4+[(1-\epsilon_r)/\epsilon_r](T_t^4-T_b^4)}. \tag{11}$$

If $\epsilon_b=1$ and $\epsilon_r=1$, then we return to our original Eq. (1).

From Eq. (10) it is seen that if the receiver surface is a blackbody, but the comparison body is not, then values of ϵ_t, if computed from Eq. (1) should be multiplied by ϵ_b in order to obtain true values. On the other hand, from Eq. (11), if the comparison surface is truly a blackbody and the receiver surface is not, values of ϵ_t, if computed from Eq. (1), are again too high, but the correction becomes rapidly smaller as either the receiving surface or the test surface approaches blackbody conditions. It is therefore evident that an uncorrected departure from blackbody conditions by the receiver surface would cause a smaller error than an equal departure by the comparison surface.

Rightly viewed, the real marvel is that we encounter natural laws at all which are the same for men of all races and nations. This is a fact which is by no means a matter of course. And the subsequent marvel is that for the most part these laws have a scope which could not have been anticipated in advance.—MAX PLANCK, The Meaning and Limits of Exact Science. (*Science* **110**, 319 (1949).)

Wilson Cloud Chamber

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THE Wilson cloud chamber described in this article has been used for the past two years as a demonstration device in general physics. It was patterned after one of the early models constructed in our cosmic-ray laboratory. Therefore, I wish to express my appreciation to Drs. E. Lofgren, E. Ney, and F. Oppenheimer for their helpful suggestions and advice.

A schematic diagram of the chamber appears in Fig. 1. A glass cylinder having a wall thickness of three-eighths inch, length of eight inches, and diameter of twelve inches fixes the size of the front compartment *A*. The window is a Pyrex glass disk twelve inches in diameter and $\frac{1}{2}$ inch thick. The back of compartment *A* is a brass plate of the same diameter and $\frac{1}{2}$ inch thick. A large number of $\frac{1}{2}$-inch holes is drilled in the plate, leaving a rim approximately $\frac{1}{2}$ inch wide intact. Compartments *A* and *B* are connected to the outside through a hole on the side of the brass plate. Black velvet is attached to the front side of the brass plate to furnish a dark background for the tracks. A wire screen (18 mesh or similar) is tied to the back side of the plate. This screen keeps the rubber diaphragm from being forced into the holes on the plate during the compression.

The maximum pressure to which the helium gas in compartments *A* and *B* can be raised is fixed by the size of chamber *B*. In the apparatus described here, the length of compartment *B* is one and one-fourth inches.

Compartments *B* and *C* are separated by a rubber diaphragm. When gas under pressure is admitted into *C* the rubber diaphragm moves in the direction of the brass plate, compressing the helium gas in compartments *A* and *B*. There are several ways of controlling the compression. A reducing valve operating off a compressed air line is one of the simplest arrangements for controlling the compression. Lately, however, we have been using helium gas for the compressions because the escape time is slightly less for helium than for air and a helium tank with a flow valve attached is a standard piece of demonstration equipment. The helium tank arrangement makes it possible to demonstrate the cloud chamber in rooms, either off or on the campus, where compressed air is not available.

Although the back plate of compartment *C* of our chamber is stamped from an aluminum sheet, a flat brass plate will do equally well. One port on this plate is necessary in making a connection to the reducing valve. A second and much larger opening allows the compressed gas in *C* to escape quickly during the expansion. An electromagnetic valve is used to control these expansions. The valve and the coil mounting are made of Armco ingot magnetic metal. The coil of the electromagnet has approximately two thousand turns of No. 30 enameled copper wire and is energized by two dry cells. A spring concentric to the guide rod of the valve is used to return the valve to its normally closed position.

The radioactive source is principally polonium. An old radon bulb was smashed and a small fragment was glued to the end of the L-shaped rod. A Geiger counter was used to obtain a source of the desired strength. After a few trials a source with an average emission of four to six alpha-particles per expansion was obtained. Figure 2 shows typical alpha-ray tracks.

The clearing field is set up between the brass plate and an aluminum ring on the inside of the window (see Fig. 1). The aluminum ring was cut out of a sheet of aluminum foil and glued to the inside of the window. Actually, we are using a fine

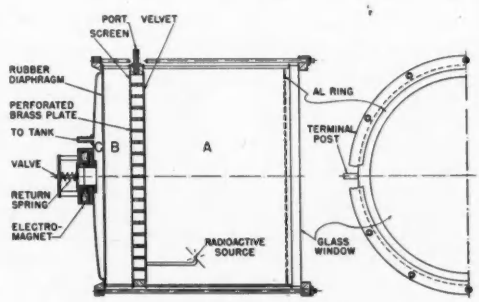

FIG. 1. Schematic diagram of the Wilson cloud chamber.

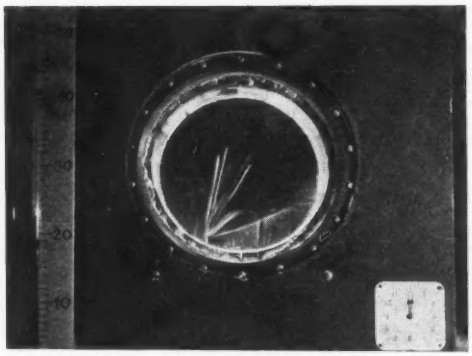

FIG. 2. Alpha-ray tracks. (Exposure time, 2 sec.)

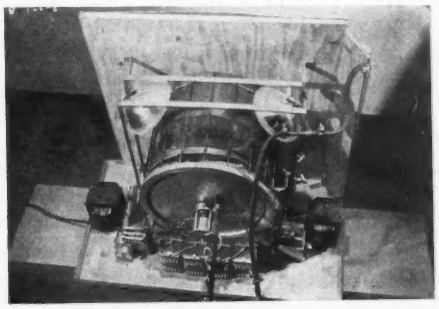

FIG. 3. Rear view of Wilson cloud chamber.

tungsten wire (No. 36 or similar) in conjunction with the aluminum ring. This wire is glued to the inside of the window, running centrally and horizontally in the assembled chamber. Both the tungsten wire and a tag on the aluminum ring are brought out and connected to the positive terminal of a 300-volt minimax battery. The negative terminal of the battery is connected to any convenient point on the brass plate.

The inside walls of compartments *A* and *B* and those pieces that are mounted within these compartments are washed thoroughly with pure ethyl alcohol before assembling. Three rubber (pure gum arabic) gaskets are needed between the metal-glass and glass-glass surfaces (see Fig. 1). The various pieces are mounted one on top of the other and clamped firmly together by two metal rings and eighteen rods.

The assembled chamber is evacuated and filled with helium gas to a pressure of one atmosphere. A solution of water and pure ethyl alcohol (7 cc of water and 3 cc of alcohol) is added to *A* and *B* after the compartments have been filled with helium gas. An open tube manometer of sufficient range to indicate the change in pressure in compartment *A* is mounted alongside the chamber as an integral part of the apparatus.

The pressure at which the chamber operates is fairly well fixed. Any deviation in operating pressure may be attributed to a temperature change. The chamber described here operates at approximately ten centimeters of mercury above one atmosphere.

The chamber is illuminated by four sealed-in auto lamps mounted at the corners of a square concentric to compartment *A* (see Fig. 3). The front half of *A* is blocked off by a strip of dark paper. Two transformers are used to supply the necessary current for the four lamps.

Once the reducing valve has been adjusted to give a satisfactory pressure, the chamber operates automatically. A set of cams attached to the shaft of an electric clock motor serves to close the light switch a few seconds before the expansion and open the electric circuit that controls the valve. The apparatus is adjusted to give one expansion per minute. Since the compression time is kept at approximately 20 sec, 40 sec are allowed for the chamber to assume temperature equilibrium.

Rolfe's new method of curing tobacco and Einstein's theory of relativity were both scientific achievements in the sense that each was an approach to thitherto unknown truth. But Rolfe wanted tobacco, while Einstein was content with the truth. To this day the typical American scientists want tobacco, and only here and there one is content with truth.—GERALD W. JOHNSON, *Our English Heritage.*

An Electronic Magnifier for Observation of Infra-Red and Ultraviolet*

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IN the early 1930's, many investigators applied image tubes to the study of infra-red reflecting and absorbing properties of materials.[1–3] They attached an image tube to a microscope or telescope and observed the object when illuminated with infra-red light.

During World War II, the image tube was considerably improved in its physical and electronic performance and was used as an infra-red-visible light transforming device in different types of snooperscopes and sniperscopes. These instruments enabled the observation of the enemy illuminated by an infra-red search light without the observer being seen.[4, 5]

In 1947, Z. V. Harvalik[6] described an electronic eyepiece attached to a spectroscope that enabled the direct observation of the infra-red portion of the spectrum. In 1948, R. Bailly[7] showed how to use the image tube in connection with the microscope, and applied it to petrographic research.

After declassification of the improved image tubes,[8] the author attempted to find uses for these in physical and chemical research. Stimulated by the fact that some substances display special properties in filtered ultraviolet light, he felt that similar procedures could be followed by using filtered light in the infra-red region of the spectrum. Because the infra-red light is not visible to the human eye, certain converting devices have to be used. Originally, only photographic plates and bolometers were utilized. However, with the development of the image tube a significant improvement in such converting devices was made.

The techniques involved in the transformation of infra-red light into visible light by the use of the image tube are as follows: The sample or specimen, illuminated by an infra-red light source (150-w projector bulb inserted into a light-tight box (Fig. 1, left) and equipped with an infra-red (Corning No. 254) filter will reflect a certain amount of infra-red light. The infra-red light reflected from the sample reaches the electronic magnifier (Fig. 1, center) where an optical (infra-red) image is focused upon the photo-cathode *PC* of the image tube (Fig. 2). The electrons released by the photo-cathode are electron-optically focused by the rings R_1, R_2, R_3, R_4 upon a fluorescent screen which is covered with a phosphor of a composition similar to that of the phosphor used in cathode-ray tubes. When the electrons reach the phosphor of the screen *SC*, they activate it to a greenish luminescence characteristic of the phosphor. The electron image formed on the screen *SC* is observed through a magnifying eyepiece. This image can be photographed by a camera attached to the lens system *M*.

The electronic magnifier for observation of infra-red images (Fig. 2) consists of the image tube 1-P-25, the magnifying lens *CL* and the magnifying eyepiece *M*. The 1-P-25 tube is

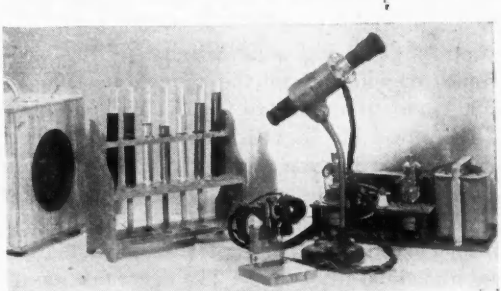

FIG. 1. Electronic magnifier.

* The electronic magnifier was exhibited at the Colloquium of College Physicists in Iowa City, Iowa, June 16, 1949. The infra-red spectroscope (Fig. 6) at the Colloquium of the College Physicists in Iowa City, in June, 1948.

† Research Paper No. 876, Journal Series, University of Arkansas.

[1] E. Brüche and O. Scherzer, *Geometrische Elektronenoptik* (Verlag Julius Springer, Berlin, Germany, 1934).

[2] W. Schaffernicht, *Zeitsch. f. Techn. Physik* **17**, 12 (1936).

[3] V. K. Zworykin and G. A. Morton, *J. Opt. Soc. Am.* **26**, 181 (1936).

[4] G. A. Morton and L. E. Flory, *Electronics* **19**, 112 (1946).

[5] G. A. Morton and L. E. Flory, *RCA Review* **7**, 385 (1946).

[6] Z. V. Harvalik, *Rev. Sci. Instr.* **19**, 254 (1948); *Bulletin APS* **22**, No. 6, 23 (1947).

[7] R. Bailly, *Science* **108**, 143 (1948).

[8] RCA Data Sheet on 1-P-25, 1944–7 (restriction removed).

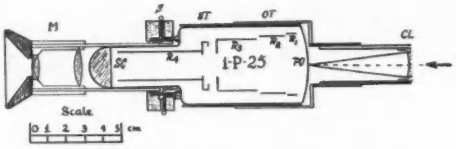

FIG. 2. Section of electronic magnifier.

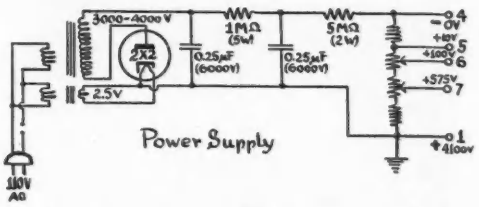

FIG. 3. Power supply for electronic magnifier.

mounted in a shielding tube *ST* of brass. The inside of the tube *ST* is lined with mica. An outer tube *OT* is slipped over the shielding tube. To this outer tube, a tube of somewhat smaller diameter is attached which holds the magnifying lens *CL*. The magnifying lens used is an $f/3.5$ Wollensack movie camera lens with iris diaphragm (not pictured in Fig. 2). This magnifying lens focuses the object on the photo-cathode of the 1-P-25 tube. The magnifying eyepiece *M*, focal length 25 mm, is mounted in a tube, slipped over the screen end of the 1-P-25 tube. A special socket *S* connects the 1-P-25 tube with the power supply.

The power supply (Fig. 3) consists of a high voltage transformer (approximately 3000-v secondary), a filament transformer for the rectifier tube 2X2 (2.5-v secondary), the filter condensers of 0.25 μf each (insulation 6000 v) and a resistor of 1 megohm, 5-w type. Due to the fact that the image tube 1-P-25 requires several potentials, a voltage divider is added to the power supply. The resistors of the voltage divider are also of the 2-w type. A neon sign transformer of secondary potential around 3000 v serves very well in the power supply.

The electronic magnifier enables one to observe light of wavelength 3000 to 4000A in the ultraviolet part of the spectrum, 4000 to 7600A in the visible part of the spectrum and from 7600A to 11,500A in the infra-red part of the spectrum. The higher sensitivity of the electronic magnifier is in the ranges of 3500 to 4500A and from 5600 to 9000A. The phosphor of the screen has its maximum radiation, when activated by electrons, around 5250A and thus is very close to the maximum sensitivity of the human eye. It has a resolution definition of 450 to 1000 lines per inch, using television standards, and a medium persistency. The magnification of the electronic magnifier, as described above, is 2.5×. It can be increased or decreased depending on the magnifier lens used, as well as on the potentials applied to the focusing rings.

Usually the electronic magnifier will be used in connection with the infra-red light source mentioned above. However, sometimes it might be desirable to observe the sample illuminated by visible light. The resulting fluorescence in the infra-red region can be observed through the electronic magnifier by placing an infra-red filter in front of the optical system, the electronic magnifier, or between the optical system and the image tube. This filter (Corning 254, 2 mm, polished) prevents the visible light from reaching the photoelectric surface of the image tube.

As already indicated, the photoelectric surface of the image tube is not only sensitive to infra-red but also to ultraviolet light. It is, therefore, understandable that the electronic magnifier can be used for other spectral ranges besides the infra-red. Ultraviolet observation can be made by illuminating the sample with filtered ultraviolet light originating, for instance, from the mercury arc. As filter, Corning No. 986 is recommended. However, because of the glass used as envelope of the image tube, an ultraviolet cut-off

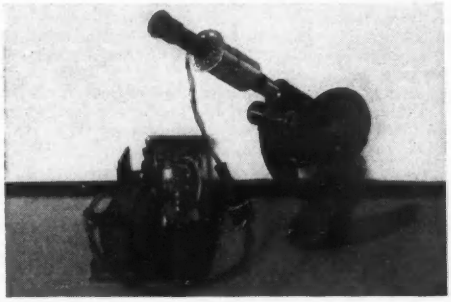

FIG. 4. Electronic magnifier used with microscope.

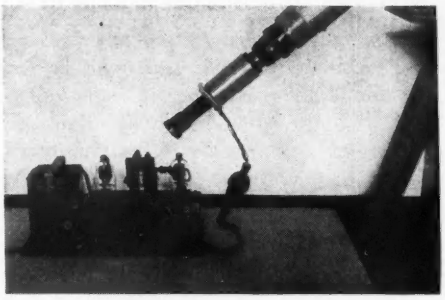

FIG. 5. Electronic magnifier attached to telescope.

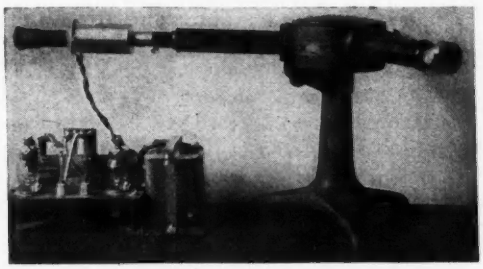

FIG. 6. Electronic magnifier attached to spectroscope.

exists around 3000A which prevents observation at shorter wavelengths.

When the magnifying lens *O* is omitted, and the image tube is attached to a microscope (Fig. 4), observations of slides in ultraviolet or infra-red light can be made. The filters can be attached to the image tube or to the light source.

The extension of visibility into the ultraviolet region and its use to identify substances or observe textures is sufficiently known and, therefore, does not need further discussion.[9] It is, of course, an understandable step to extend the visibility of the human eye into the region of infra-red when convenient devices exist to observe infra-red light. The electronic magnifier seems to meet the requirements of convenience and efficiency.

Investigations of the behavior of organic substances, especially dyes, in infra-red or ultraviolet light indicate the development of special reactions for certain elements and compounds utilizing the variations of infra-red or ultraviolet reflectivities of the reaction products. Certain natural substances, like chlorophyll, cannot be duplicated easily with respect to color properties. Synthetic dyes may deceive the human eye by suggesting green leaves or grass; however, in infra-red light, the color property of the synthetic dye will not correspond with chlorophyll, for chlorophyll reflects infra-red light very strongly while most of the dyes absorb it—something of importance for camouflage experts.

Macroscopic observations in infra-red light can be used to identify tissues, fibers, textures of natural and synthetic materials, of plant and animal tissues, important in agricultural and industrial research.

In criminology, many applications can be found for the electronic magnifier, e.g., reading a letter without opening the envelope, detection of cryptographic inks, identification of fibers and stains.

It might be possible that the electronic magnifier would develop into an important tool in vitamin and nutrition research as well as in medicine, especially pathological histology. Dr. Bailly's work already shows the importance of infra-red analysis and identification of rocks and minerals.

The image tube, attached to a telescope (Fig. 5) and supplied with a Corning 254 filter will penetrate haze. Trained at the moon it will show the infra-red pattern of the lunar surface.

Attached to a spectroscope (Fig. 6) the image tube permits the observation of spectral lines in the ultraviolet and infra-red region of the spectrum.

[9] P. W. Danckwortt, *Luminiscenz Analyse im Filtrierten Ultravioletten Licht.* (Akad. Verlagsanstalt, Leipzig, 1934).

Report of the Coulomb's Law Committee of the American Association of Physics Teachers

The report of the Coulomb's Law Committee, "The Teaching of Electricity and Magnetism at the College Level," appearing in the January and February, 1950, issues of the *American Journal of Physics* will be reprinted and bound into a pamphlet. Copies will be available to anyone interested at a nominal charge. Institutions and individuals wishing a large number of the reprints are requested to notify the Secretary, R. F. PATON, Department of Physics, University of Illinois, Urbana, Illinois, before May 1, 1950, to insure that they will be available.

The Birth of the Meson Theory*

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AND

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DURING the Symposium at the University of Michigan in the summer of 1948, the junior author had the good fortune to obtain a copy of Professor Hideki Yukawa's autobiographical sketch, a small booklet written in Japan in 1941. His name is inseparably associated with mesons and the meson theory of nuclear forces and his theoretical deductions concerning this particle in 1935 are one of the many brilliant chapters in the history of physics. The origin of the meson theory is of interest not only to those who are active in that field of research but also to those who are interested in the development of the ideas and concepts of modern physics. Because Professor Yukawa's writing is in Japanese, the writer has taken the liberty of making a free translation with the hope that English-reading physicists may have a clear appreciation of the development of the meson theory and obtain a glimpse of the life and personality of a man who gave a new idea to the world of physics. The author wishes to express his sincere appreciation to Professor H. Wergeland of the Technical Institute at Trondheim, Norway, without whose constant encouragement the translation would not have been completed.

Life in Kyoto

"I was born in Tokyo in 1907. The following year, my father, Takuji Ogawa, accepted a position at Kyoto University, and for the next twenty-odd years, until the spring of 1932, we lived in Kyoto. Although my father's field was geology and geography, he was a man of a great many interests, which included archeology, Chinese studies, art, swords, chess, etc. As a consequence, not only his study, but also the storage house and the living rooms of our home literally overflowed with books. Since we moved frequently, the ever-increasing number of books was a source of constant headache to the family. Being in this kind of atmosphere, I naturally grew up to like books and to read omnivorously. It is difficult to know exactly just what effect this kind of a home atmosphere had upon me, but probably it contributed a great deal to the fact that my life has been devoted mainly to reading, thinking, and writing.

"My father did not attempt to direct my interests. Consequently I had trouble in making up my mind about the subject to take up at the University. In the first application made out during my third year in junior college, I indicated geology as my preferred major. But when the time came to make my final decision, I suddenly changed my mind and wrote "physics" in the application blank.

"During my third year in the University, I again had a little trouble making up my mind. I finally decided to take up quantum theory and subsequently asked Dr. K. Tamaki, professor of theoretical physics, to guide my work. Professor Tamaki's principal interests then were in hydrodynamics and the theory of relativity and so perhaps he felt a little annoyed at my request. However, he gladly accepted. I studied in the pleasant atmosphere of his laboratory until 1933 when I went to the Osaka University. During this time, many were the books that I had to ask my parents to buy for me. I did not publish any results that I obtained during the four years there, but it turned out to be an extremely valuable preparatory period for my life to come in Osaka.

"When I was attending the University, it was only a short time after de Broglie and Schroedinger had published their works on wave mechanics and Heisenberg his paper on quantum mechanics. Consequently, in Japan there were

* From a chapter of Hideki Yukawa's *Me-ni-mie-nai-mono* (Of things that cannot be seen); title, introduction, and translation by Chihiro Kikuchi, Michigan State College, East Lansing, Michigan.

then no specialists in this field. So I read indiscriminately the papers on quantum mechanics as fast as they were published, although many were the times I could not understand what I was reading.

"Fortunately, just before and after graduating from the University, a number of European physicists were invited to come to Japan. First a student of Sommerfeld, Dr. Laporte, came to give a discourse on quantum dynamics for several days. Then Sommerfeld himself came to Kyoto University and gave lucid lectures on quantum mechanics. And a little later on, I had the opportunity to hear Heisenberg himself discuss the uncertainty principle and Dirac his relativistic theory of the electron. Also about this time, the Japanese physicists Arakatsu, Sugiura, and Nishina, who had returned from abroad, came to give a series of lectures. It is difficult to put into words how much I was stimulated and inspired by these lectures. I felt as if I had been entrusted with the task of nurturing the bud of new physics which they had planted in me.

Life in Osaka

"In 1932, I was adopted by Genyo Yukawa and subsequently moved to Osaka. My foster father had by then retired from a strenuous doctor's life because of a heart condition. In 1935, he passed away, knowing very little about the results of my work.

"In April of 1933, at the Sendai meeting of the Physico-Mathematical Society of Japan, I presented my first paper. The subject was, as I remember it, 'On the Theory of Nuclear Electrons.' The neutron had been discovered just a year before, and the theory that the nuclei consist of protons and neutrons was becoming better known. Those were the days before Fermi formulated the neutrino theory of beta-decay. Some people were doubting that quantum mechanics would be applicable to the nucleus, and others felt that perhaps energy was not conserved in nuclear transmutations.

"I was then trying to formulate mathematically Heisenberg's idea that the interaction between a neutron and a proton arises from the exchange of an electron. I introduced the hypothesis that the proton and neutron are the sources of the electron field. As a consequence, it was possible to obtain an expression that looked very much like nuclear forces. But I was unable to carry my idea further because the force range was too long and the electron would have to obey Fermi statistics. Dr. Nishina, who was present at the meeting, then suggested that it might be possible to postulate the existence of electrons satisfying Bose statistics. This was the first hint toward the meson theory. From that day on, Dr. Nishina took the most active part in encouraging my investigations.

"At this meeting, I was introduced to Dr. Yagi, the physics department head of Osaka University, and was subsequently invited to join his staff. This proved to be a valuable association because the physics laboratory at Osaka University had just been built and the laboratory was alive with young instructors. A Cockcroft high-voltage apparatus had just been completed. The following year Dr. S. Kikuchi was called from the Tokyo Institute of Physical and Chemical Research to direct the program on nuclear research.

"Surrounded by this active atmosphere, I was racking my brains trying to solve the difficulties that I mentioned before. In the meantime, Fermi published his theory of beta-decay. His theory differed from mine in that an electron-neutrino pair was used. In this way he was able to remove the statistics difficulty, but his theory, like mine, could not account for nuclear forces and beta-decay simultaneously.

"In the fall of 1934, when my second son was born, I became so engrossed in thinking about nuclear forces, that I began to find it difficult to fall asleep at nights. My mind would become clearer and clearer, and one idea after another would race through my mind. And so not to forget them, I kept a note pad at my bedside and jotted down the ideas as they came to me. But the next morning when I went over the notes, I had the strange experience of not being able to make sense of the ideas that seemed so clear to me the night before. Anyway, after repeated attempts of this kind, my ideas of the nuclear force field began to crystallize and so I was able in October to present my ideas at a seminar. I concluded that in this new field the rest mass of the new quanta should be about two hundred

times the electron mass and obey Bose statistics. At that time, Dr. Kikuchi[1] commented that the new quanta should carry electric charge, and therefore if such particles do exist, the particles should be observable in cloud chambers. However, because it would be difficult to create such particles in the laboratory, perhaps one should look for them in cosmic rays. But, at that time, very little was known about the nature of cosmic radiation.

"At the Tokyo meeting of the Physico-Mathematical Society of Japan, I presented my new theory, and in the following year, in February 1935, the paper was published in the Proceedings of the Society. I wish to thank my fellow physicists for showing their interest in my theory and particularly Drs. Nishina and Kikuchi for their encouragement, although it was difficult to accept the theory *in toto* without experimental evidence.

"The theory was thus constructed but experimental evidence was still lacking. The following year, in 1936, C. Anderson, the discoverer of the positron, reported having observed an unusual particle in a cosmic-ray cloud-chamber photograph of mass intermediate between that of the electron and of the proton. Upon reading this report, I immediately concluded that this must be the new particle I had been looking for. However, it now appears that the particle that Anderson observed was not an ordinary meson, because its mass appears to be much closer to the proton mass. The identity of that particle is still a puzzle. In the years 1937 and 1938, clear-cut evidence of mesons was obtained in the United States by Anderson, Street, and others; in other countries; and in Japan by Nishina.

"Finally, I wish to add that a greater portion of the credit for the development of the meson theory since 1937 should go to those who explored the various aspects of the theory. Notably, Dr. Sakata (Nagoya University) solved one knotty problem after another. I am also greatly indebted to the efforts of Dr. Kobayashi (Kyoto University) and Mr. Taketani (Tokyo Institute of Physical and Chemical Research). Later, a number of young men tackled different aspects of the problem. And I owe a great deal to many theoretical physicists in Europe and in the United States, who developed the theory more or less independently of the Japanese physicists. So I feel embarrassed when I am given the sole credit for the development of the meson theory.

"The meson theory today is at an impasse. If I succeed in solving the difficult problems of the theory, I will have repaid, in a small way, my indebtedness to my parents, to my teachers, and to all my friends in Japan and in other countries. · · · November, 1941, Kyoto, Japan."

[1] Not to be confused with the translator, C. Kikuchi.

Colloquium for College Physicists

The annual June meeting, 14th to 17th, of the Colloquium of College Physicists will have the following features: An evening exhibit of new devices with award of prizes, research reports from members, research lectures by Dr. H. C. UREY, Dr. KATHARINE B. BLODGETT, Dr. JOHN SPENCE, Dr. ROBERT L. SINSHEIMER, and round table discussions of Laboratory led by Dr. ANDREW LONGACRE, and of physics history for nonscience students led by Dr. DUANE ROLLER. An addition to the program of this year is an associated course of four lectures prepared for college physicists by Dr. EDWARD TELLER, and sponsored by the Research Foundation. The title of the lectures is "Hydrodynamics in Cosmic Physics." The meeting is at the State University of Iowa at Iowa City, Iowa, and begins Wednesday afternoon, June 14th. Requests for final programs should be sent to G. W. STEWART at the University of Iowa.

What the Student Thinks

ROLAND E. MUESER
The Pennsylvania State College, State College, Pennsylvania

THE college student, although perhaps a biased and inexperienced critic, is in a unique position to judge teaching aptitude. By necessity he must become intimate with the material of a course and since the object of its presentation is his learning, he is highly qualified to give an opinion on how well the job is done. In addition, since most instruction is repetitious, the powerful tool of the statistical approach is available in interpreting such opinion.

There are a number of reasons why relatively little has been done in soliciting student opinion concerning teaching: The subordinate position of the student acts to bias his judgment and special care must be taken to obtain an objective attitude. Furthermore, university educators are often chosen on a basis of their scholarly rather than teaching abilities. Thus, it is neither easy nor materially very rewarding for the teacher to encourage student criticism—especially when it may be negative. On the other hand, an instructor anxious to measure his success at generating interest will want a more accurate indicator than grades or a count of dozing students.

An experimental poll of students has, therefore, been made in an effort to analyze opinion of a single electronics course. This paper is a report of an attempt to make and interpret such a survey.

An Experimental Survey

A questionnaire soliciting student opinion was circulated as part of the final examination in an electronics course at the end of each of two semesters. The course was for juniors in the department of electrical engineering at The Pennsylvania State College. The final examination period is too much a time of stress for ideal polling; however, the practical advantage of having the student available was considered greater than the possible coloring of answers because of circumstances. Opinion sheets were distributed to four classes of approximately 20 students each, taught by the same instructor. A reproduction of the questionnaire is attached as an Appendix.

The specific answers to the questionnaire are important only to the teacher. However, some over-all statistics from the survey are of general interest.

In Question I, the student reported his difficulty with various portions of the course. From the responses it is possible to evaluate difficulty as a function of student grade. Except for the top students who found the course slightly easier, all students rated it of the same difficulty. However, if the difficulty of the course is judged only by the student evaluation of tests, quizzes, and exams, the results are more as expected (Fig. 1). It is reasonable that the student's grade should correlate better with reaction to testing than with his general opinion of the work.

When asked about the difficulty of practical applications covering survey material, the work was considered "easy" with little variation between students. However, in the case of theoretical work, a significant reverse in rating resulted (Fig. 2). An explanation for students rating this inversely proportional to their grades is that the theoretical material went completely over the heads of the poor students, hence was

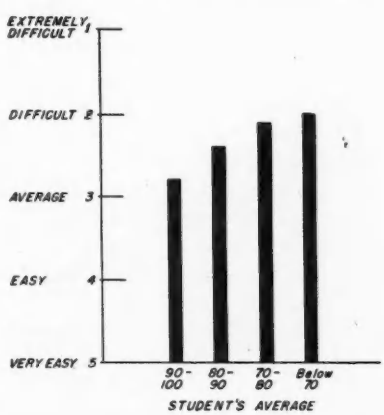

FIG. 1. Relationship between students' grades and their estimates of the difficulty of tests and examinations in an electronics course.

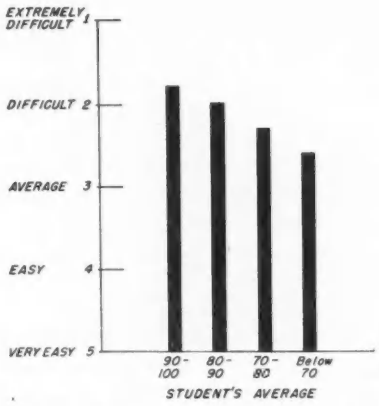

FIG. 2. Relationship between students' grades and their estimates of the difficulty of theoretical work in an electronics course.

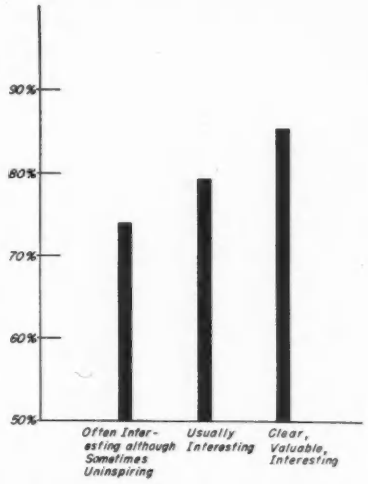

FIG. 3. Correlation between students' grades and their over-all opinion of a course in electronics.

not sufficiently grasped to judge its actual content. Comparison of the bar-graphs, Figs. 1 and 2, indicates a variation of less than 10 percent from class to class.

In response to Question V asking how they liked the course, the students filled in only the last three categories. Here is evidence that *a student does well when he likes the course* and *vice versa* (Fig. 3). It cannot be stated which is cause and which is effect, but the replies re-emphasize the importance of a student's interest in his work.

Questions I–IV were also used to modify the presentation of material before giving the course again. In this manner it was possible to obtain positive evidence of the effect of changes. For example, the number of students voicing the objection that too much material was covered dropped from 50 to 5 percent by leaving out, during the second semester, a section of the course on frequency response of amplifiers.

Despite the small size of the statistical samples, some interesting hypotheses are possible: Since the students participating were college juniors, they had established college averages, i.e., average grades based on all previous courses taken. If this average in percent is plotted against the final grade in the course, Fig. 4 is obtained.[1] The dotted line and region to its right includes those students who exceeded their college average in the electronics course. The solid line of regression, or best fitting straight line, is quite different. It would appear that on an average the best students equalled or surpassed their college average. On the other hand, the poorer the student was, the more he fell short of this average. Such a distribution may be indicative of the comprehension level on which the material was presented. Apparently, the course was enough of a challenge to interest the good students, but over the heads of the poor students. It implies a failure in many students to grasp new fundamental concepts while nevertheless riding along with little trouble over the bulk of engineering survey material. Apparently, many top students also worked harder than usual and those with low grades did not exert themselves. The angle between the two lines might, therefore, be considered an indication of the level of instruction. A very difficult course would increase the angle while a "snap" might very conceivably lead to a negative angle, i.e., enable the poor student to do better than usual, while prohibiting (and probably not inspiring) like improvement in the best student. It should be pointed out that the intercept between the two lines is a function of the curve on which the course is graded, but that any constant per-

[1] The sample contains all cases including those where widely diverse maturity and experience (such as previous military electronics training) account for many of the outlying points.

centage applied to all grades equally will not influence the slope of the best fitting line.

On the basis of answers to Question III, average preparation time is plotted against grade in Fig. 5. The wide range of previous experience and aptitude is immediately apparent, thus the correlation coefficient is low. The graph is divided into arbitrary regions since the student's classification of aptitude is dependent both on his mark and preparation time. It is hoped, some day, to make engineering aptitude tests that will discover if students of like aptitude can be divided in regions as depicted.

In this study a plot was also made revealing only slight correlation between student evaluation of difficulty and his study time. Neither did relative study time correlate with grade improvement or deterioration (with respect to his college average) in the electronics course. Apparently the wide range of aptitude makes it difficult to uncover significant grouping of such data without dividing larger samples into aptitude categories.

Conclusion

An analysis of student opinion may be helpful to the instructor because it can be used as a guide to his manner of presentation. It also allows a study of the suitability of the content organization. It should benefit the student, particularly in technical courses where the *concept* is very important. Furthermore, such a study may bring to light unrecognized characteristics of the college student's educational behavior. Certainly his educational opinions and habits should not be overlooked at a time when the demand for college education is higher than ever before in history.

Appendix

Electronics Course Opinion Sheet

This question sheet is for your opinions about the course and is distributed so you may give me the benefit of your experience and ideas. In order to make certain statistical correlation analyses it would be helpful if you would be willing to include your name on the sheet. However, these sheets will be sealed and filed away *until after* final grades are handed in so your final mark will bear absolutely no relation to what you say here. Furthermore, after the sheets are studied, no individual but rather only the overall statistical results will be recorded. I would, therefore, appreciate it if you would be honest and considerate in your answering.

I. Let the following numbers stand for your evaluation of difficulty and then insert the appropriate one after each phrase:

(1) Extremely difficult
(2) Difficult
(3) Average
(4) Easy
(5) Very easy

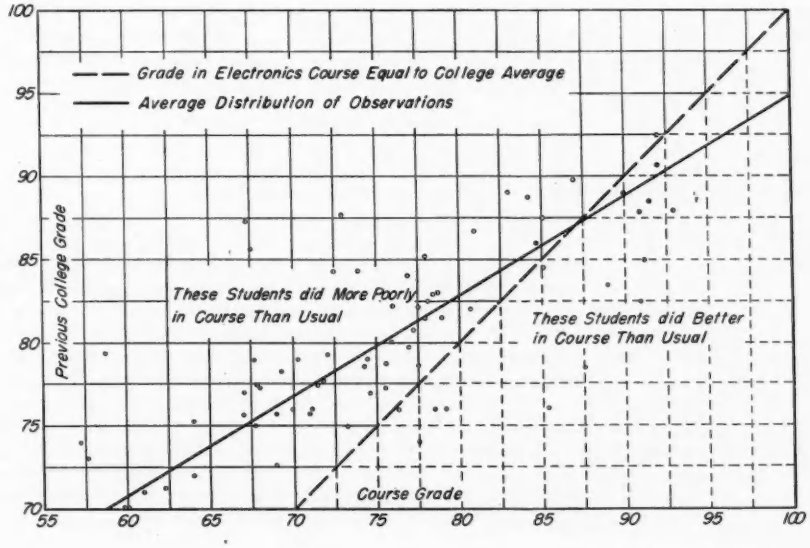

FIG. 4. Comparison of students' grades in a single electronics course with their averages from all previous college work.

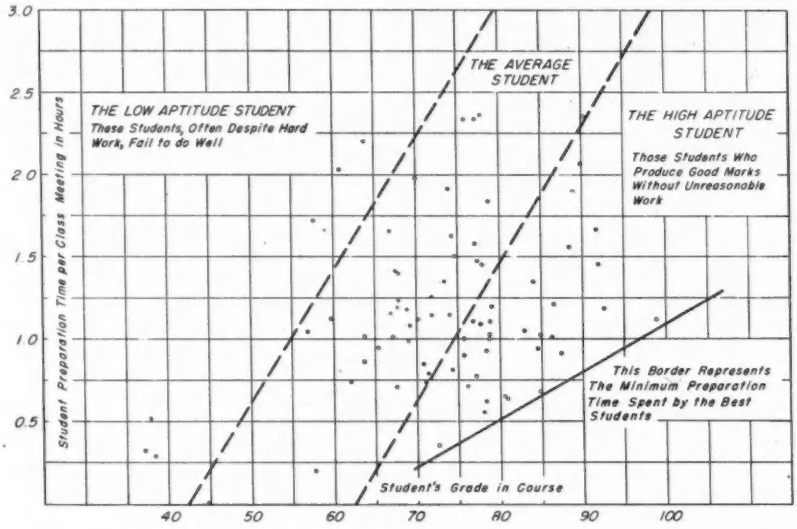

FIG. 5. Distribution of students as a function of their average preparation time per class and final grades in an electronics course.

In the second column please put down the letter indicating whether you would like less (L) the same (S) or more (M) time spent on the subject.

1. Electron gas theory of metals ( ) ( )
2. Diodes, triodes and multi-electrode tubes ( ) ( )
3. Audio amplifier, gain, distortion, feedback ( ) ( )
4. Special tubes, magnetron, television, etc. ( ) ( )
5. Gas theory ( ) ( )
6. Commercial gas tubes ( ) ( )
7. Short quizzes ( ) ( )
8. Hour exams ( ) ( )
9. Homework assignments ( ) ( )
10. The textbook ( ) ( )
11. The course, taken as a whole ( ) ( )

II. 1. What section, topic, or lecture did you like most?————
2. Like least?————
3. Would you emphasize theory and fundamentals more, or devices and applications more, or keep the ratio about the same?————

III. 1. How long, on an average, did you spend reading, studying, and doing homework for each classroom meeting? ——— hours.
2. How many hours did you spend studying for the final? ———

IV. 1. On a whole, do you think the marking system was fair? ———

V. Check the statement which expresses your feeling of the course most accurately.
( ) An unpleasant but necessary evil
( ) Dull but passable
( ) Often interesting but sometimes uninspiring
( ) Usually interesting
( ) Clear, valuable, interesting

VI. On the back of the page make any additional comment. What you have to say will be appreciated regardless of whether it is favorable or unfavorable.

It is very noteworthy that in the fifteen years between Maxwell's publication of his work on Electricity and Magnetism and Hertz's discoveries a great deal had been written about "Maxwell's theory" and in particular concerning the electro-magnetic theory of light, and these subjects had been lectured upon at universities, yet not even the beginning of a way to the goal had been made clear, for people simply played about with Maxwell's equations, but not with the ideas of Maxwell or Faraday; it was a mathematical game and not scientific research that was pursued, and the results were sterile. Hertz was the first who not only understood the equations, and knew how to deal with them mathematically when necessary, but also saw the structure of ideas upon which they were based by their originator, and understood how to move about in it. The equations are, so to speak, merely ground plans of this structure, and are far from being actual inhabitable apartments; the latter can only be produced by the architect, who knows how to grasp the ideas which have been put into the ground plan.—Great Men of Science, PHILIPP LENARD, p. 359.

NOTES AND DISCUSSION

Wiener's Experiment: Stationary or Progressive Waves?

JOSEPH W. ELLIS
University of California, Los Angeles, California

IT seems to be traditional for the authors of college textbooks in optics to refer to Wiener's experiment, in which the angle of incidence i of the light waves is greater than zero, as an example of stationary waves without qualifying the statement. It is true that there are nodal and antinodal surfaces parallel to the reflecting surface. But the second fundamental characteristic of stationary waves, that there be time values at which displacements are zero at all points in the space occupied by the incident and reflected waves, is lacking. The motion has aspects of both progressive and stationary waves, as the following discussion shows.

Let (x, y) be the reflecting surface. Let z be normal to this surface and (x, z) the plane of incidence. The direction cosines associated with x and z may be designated as $(l, -n)$ and (l, n) for the incident and reflected wave normals, respectively. Assume that the light is plane polarized in the plane of incidence, i.e., that the electric displacement vector, represented by Y, is perpendicular to this plane. The motion resulting from the superposition of the two sets of plane waves is given by

$$Y = A\sin 2\pi\left(\frac{lx-nz}{\lambda}-\frac{t}{T}\right)+A\sin 2\pi\left(\frac{lx+nz}{\lambda}-\frac{t}{T}-\frac{1}{2}\right)$$

$$= 2A\cos 2\pi\left(\frac{lx}{\lambda}-\frac{t}{T}\right)\sin\frac{2\pi nz}{\lambda}$$

$$= 2A\cos 2\pi\left(\frac{x}{\lambda/l}-\frac{t}{T}\right)\sin\frac{\pi z}{\lambda/2n}.$$

The phase reversal at the reflecting surface has resulted in the introduction of $-\frac{1}{2}$ in the argument of the second wave expression. The usual but incorrect assumption of equal amplitudes A in the incident and reflected waves has been made.

From the above development we see that a progressive wave of increased wavelength λ/l travels in the x direction with a speed v equal to λ/lT. Nodal planes parallel to the (xy) surface exist, with spacings Δz equal to $\lambda/2n$. Two limiting examples exist: $i=0°$ and $i=90°$. As i approaches zero the progressive wavelength and speed approach infinity and there exists in the limit a completely stationary state with nodal planes separated by $\Delta z=\lambda/2$. As i approaches 90° the progressive wave speed approaches that of the incident wave, λ/T; the spacings of the nodal surfaces approach infinity. Before this latter limit is reached, however, the phenomenon goes over to Lloyd's mirror interference, as Wood[1] has pointed out. The separations of interference fringes, i.e., of nodal planes, is large enough to be detected with the eye.

Joos[2] in his chapter on the theory of vibrations and waves, and Rayleigh,[3] dealing with acoustic waves, have discussed, with treatments similar to the above, the motion resulting from the coexistence of two sets of plane waves inclined to each other. The interpretation of Joos is particularly interesting, namely, that the motion is one of a space-modulated progressive wave. If the waves are electromagnetic, the Poynting vector is, of course, also space-modulated. Another statement of the result is that the planes of equal amplitudes are perpendicular to the planes of equal phases. The analysis and ideas presented in the present paper are familiar to those people who have analyzed the simpler modes of microwave transmission in rectangular wave guides.

[1] R. W. Wood, *Physical optics* (Macmillan, New York. Ed. 3, 1934), p. 214.
[2] G. Joos, *Theoretical physics* (Stechert, New York, 1934), p. 60.
[3] Rayleigh, *The theory of sound*, Vol. II (Dover Publications, New York, 1945), p. 76.

Calcite Crystal Model

F. E. CHRISTENSEN
University of Minnesota, Minneapolis, Minnesota

THE model described here was constructed to demonstrate before large classes the propagation of light through an optically active crystal of the calcite type. The model illustrates only the case in which light enters the crystal at perpendicular incidence. This simplifies the mechanical construction.

The crystal is represented by two sheets of Lucite ($36\times11\times\frac{1}{4}$ in.) separated $\frac{1}{2}$ in. An arrow is mounted at one end of the "crystal" to indicate the orientation of the optic axis relative to the incident surface and the incident light. It is possible to rotate this arrow through an angle of 90° so that one can show the effect upon the rays traversing the crystal when the optic axis is perpendicular to, or in the same direction as, the incident beam and at some intermediate angle.

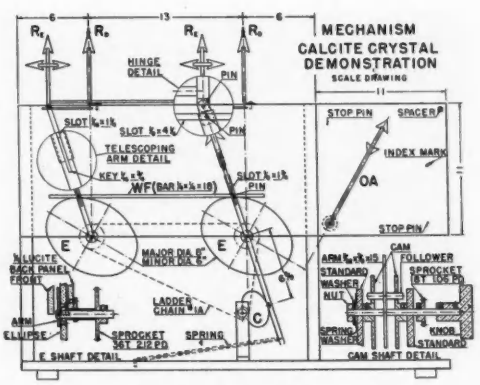

FIG. 1. Diagram of calcite crystal model.

The ellipses E (see Fig. 1) are made of Lucite and are mounted with their centers at the surface of the crystal. A band $\frac{1}{4}$ in. wide is painted on the rim of each ellipse to show the envelope of the velocity vectors of the extraordinary ray. A ladder chain connects the ellipses and the cam assembly. A knob attached to the cam axle controls the rotation of the ellipses and the rod representing the direction of propagation of the extraordinary ray through the crystal. The wave front WF of the extraordinary ray R_e is represented by a bar free to ride on the surfaces of the ellipses.

The direction of the extraordinary ray within the crystal is represented by a telescoping arm. The direction and polarization of the emergent extraordinary ray are shown by appropriate arrows.

The arrangement for showing the propagation of the ordinary ray is not indicated in the detailed drawing. About the center of each ellipse there is painted a 6-in. semicircle. This semicircle is a band $\frac{1}{4}$ in. wide painted on the inside of the front Lucite sheet to represent the envelope of velocities of the ordinary ray within the crystal. Similarly, a band tangent to the semicircles and a band perpendicular to the crystal face through the centers of the semicircles are painted on the Lucite sheet to represent the wave front and direction of propagation, respectively. Arrows showing the direction of polarization are attached to rods which represent the emergent ordinary ray.

Two colors of paint are used to distinguish the parts of the apparatus associated with the ordinary ray from those associated with the extraordinary ray. Figures 2 and 3 show front and rear views, respectively, of the completed crystal model.

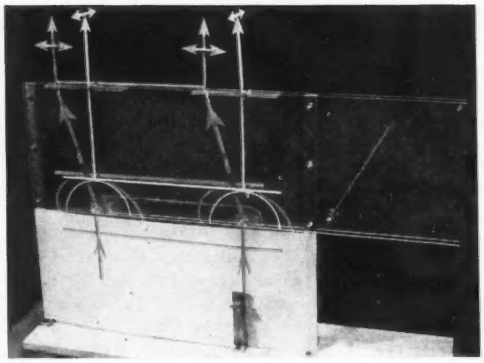

FIG. 2. Calcite crystal model—front view.

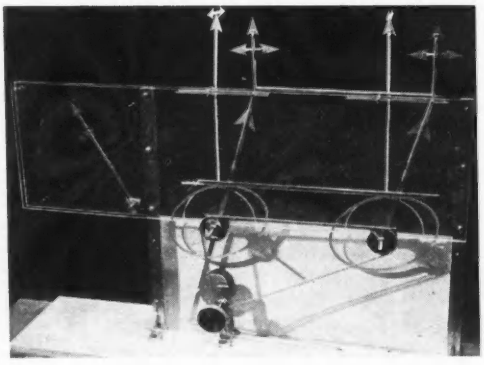

FIG. 3. Calcite crystal model—rear view.

Nomenclature Policy in Radiometry and Photometry*

A. G. WORTHING†
University of Pittsburgh, Pittsburgh, Pennsylvania

MANY physicists will agree that it is highly desirable with regard to nomenclature policy to adopt certain consistent principles and to adhere to them rather rigidly. Among these principles are three which stand out in the present discussion. (1) The root word for a group of terms should be as suggestive of the group as possible. (2) The term endings should be in accord with a consistent policy. (3) A single term should not have a natural connotation different from that to which it is assigned. Regarding the first-named principle, there is agreement, but regarding the other two there seem to be differences of opinion in different groups.

At the request of The Optical Society of America, The American Standards Association (ASA) established a committee, ASA Z-58, for the purpose of standardizing terms, definitions, procedures, and devices in the field of optics, including radiometry and photometry. In accord with its general policy, the ASA will seek, through committees, to develop tentative standards in the requested fields, to determine their acceptability to those interested and, if found acceptable, to publish such findings as accepted standards. Such published findings will carry great weight.

Professor F. W. Sears of the Massachusetts Institute of Technology is Chairman of ASA Z-58 as well as of its Subcommittee 1, which is concerned with nomenclature in radiometry and photometry. Following the receipt of suggested sets of terms for radiometry and photometry, Professor Sears submitted appropriate material to the subcommittee for their consideration. The last column of Table I is a part of the material submitted. This list, marked OSA, is substantially the same as that published by the Colorimetry Committee of the Optical Society of America. The list of terms given in the next to the last column of the table, marked RSI, is practically the same as one published by another committee in *The Review of Scientific Instruments*.[1]

The divergence of opinion of the two groups with regard to principles underlying nomenclature policy is well illustrated in lines 4 through 9.

TABLE I. Comparison of proposed terms for radiometry and photometry.

		Definition	mks unit	RSI A consistent set of terms, sponsored by Prof. Worthing		OSA Proposed standard submitted to members of Z-58 by Prof. Sears	
1	In general	Energy of electromagnetic waves	joule	Radiant energy Luminous energy	U Q	Radiant energy Luminous energy	U Q
2		Energy per unit volume	$\frac{\text{joule}}{\text{m}^3}$	Radiant energy density Luminous energy density	u q	Radiant density Luminous density	u q
3		Energy flowing per unit time (total flux)	watt	Radiance (radiant flux) Luminance (luminous flux)	P F	Radiant flux Luminous flux	P F
4	From a source	Flux per unit solid angle	$\frac{\text{watt}}{\text{steradian}}$	Steradiance Sterluminance	J I	Radiant intensity[a] Luminous intensity[a]	J I
5		Flux per unit area	$\frac{\text{watt}}{\text{m}^2}$	Radiancy Luminancy	$\mathfrak{R}$, W L	Radiant emittance Luminous emittance	W L
6		Flux per unit solid angle per unit area	$\frac{\text{watt}}{\text{steradian-m}^2}$	Steradiancy Sterluminancy	N B	Radiance Luminance	N B
7	For a surface	Flux per unit area arriving at a surface	$\frac{\text{watt}}{\text{m}^2}$	Irradiancy Illuminancy	H E	Irradiance Illuminance	H E
8		Fraction reflected	—	Radiant reflectivity Luminous reflectivity	ρ r	Radiant reflectance Luminous reflectance	ρ r
9		Fraction transmitted	—	Radiant transmissivity Luminous transmissivity	τ t	Radiant transmittance Luminous transmittance	τ t
10		Fraction absorbed	—	Radiant (surface) absorptivity Luminous (surface) absorptivity	α a		
11		Fraction emitted	—	Radiant emissivity Luminous emissivity	ϵ e		

[a] See reference 4.

As matters stand at present, the OSA terms have been approved by the nomenclature subcommittee and will be submitted to the complete ASA Z-58 Committee for its approval some time in the future.

There are certain endings (not illustrated in Table I) namely those associated with processes, *-ion*, and devices, *-or*, concerning which there seems to be general agreement.[2] Thus we have the process terms radiation, irradiation, transmission, reflection, absorption, and emission, and the device terms radiator, reflector, absorbor, and emittor. There are certain other endings, namely those associated with measurable physical quantities or characteristics, *-ance*, *-ivity*, or *-ity*, and *-ancy* concerning which there is divergence of opinion at the present time.

An *-ance* ending has been reserved by custom for the property of a body or of a device or portion thereof and an *-ivity* or an *-ity* ending for the property of a substance. We speak of the resistance and the electrical conductance of a particular wire and of the resistivity and the electrical conductivity of the substance of which it is composed. Other *-ance* terms for some of which there are corresponding *-ity* terms are admittance, capacitance, conductance, inductance, permeance, reactance, reluctance, remanance, susceptance, thermal capacitance, thermal conductance, thermal resistance.

The *-ancy*[1] ending was first published in 1936. It is applicable particularly to the fields of radiometry and photometry, and was intended to indicate a property expressible in terms of "*per unit area*" or "*per unit of depth or of thickness*" with the understanding that in any instance one usage or the other would be obviously inapplicable. The RSI terms of lines 5, 6, and 7 of Table I, namely radiancy (luminancy) of a source, steradiancy (sterluminancy) of a source, and irradiancy (illuminancy) of a surface are illustrations of the "per unit of area" characteristic. The other usage for an *-ancy* ending, namely "per unit of depth" does not occur in the abbreviated Table I. Certain usages, however, have already received ASA approval.[3]

Returning to the question of desirability of terms, consider the terms of line 5, namely radiant (luminous) emittance and radiancy (luminancy) of a source. Describing a blackbody source at 2000°K, users of OSA terms would say that it has a *radiant emittance* of about 4600 kw/m² as though this value does not depend in any way on the area of the blackbody source as would normally be expected from the *-ance* ending. On the other hand, users of the RSI terms would say that its *radiancy* is about 4600 kw/m² with the understanding that the *-ancy* ending indicated an area characteristic. Similar comparisons may be made for the terms of lines 6 and 7.

The OSA terms of lines 5, 6, and 7 of Table I are undesirable because of a failure to adhere to principle No. 2, as listed previously, which concerns a consistent ending-policy. According to one of the chief proponents of the OSA terms, ". . . the suffix *-ance* is used in all terms referring to properties of devices but it is not confined to such terms. It is used in several of the names for quantities in preference to less euphonious endings." *The basis for choice between the* OSA *and the* RSI *terms is thus narrowed down to one of euphony versus consistency for term endings.*

Principle 3, as listed, is also violated by the OSA term policy. As OSA terms, radiant (luminous) reflectance and radiant (luminous) transmittance are listed in lines 8 and 9.

OSA terms for the similar properties involving absorption and emission, however, were not mentioned in the proposed standard submitted to members of Z-58 by Professor Sears. For them RSI terms are naturally radiant (surface) absorptivity and radiant emissivity. They are needed terms in radiometry.

Frequently it is said that the radiant (surface) emissivity is equal to the radiant (surface) absorptivity. That, however, is only true when the frequency distribution of the incident radiant flux is like that from a blackbody at the temperature of the absorbing body. This condition is ordinarily *not fulfilled* when radiant absorptivities are measured. Obviously, to go along with the terms radiant reflectivity, and radiant transmissivity, the terms radiant absorptivity and radiant emissivity are needed. With these terms, with which the writer is well satisfied, the OSA recommendation for the quantity measured in watt/m[2] is highly inconsistent.[4]

Teachers, textbook writers, and students of physics and engineering will be troubled if the OSA proposals are adopted, by the departure from standardization with regard to the *-ance* ending or by the stated and the implied meanings of the term "radiant emittance." Others not closely associated with them are also bound to be badly confused by that situation. It is not difficult to imagine what will result from having developed the significance of an *-ance* ending in the fields of heat and of electricity and magnetism only to find that the significance there given is disregarded in radiometry and photometry. In the field of science we should lead rather than just keep abreast of the layman in policies relating to term endings.

The purpose of this note is to urge that those, who read it, act at once. Align yourself as a believer either in the "euphony" or the "consistency" policy and notify Professor Sears[5] concerning your position with regard to this matter which concerns the future of scientific terminology. He will do his best to make your wants in this matter known to the ASA standardizing committee.

[3] Edited by M. W. Zemansky and H. K. Hughes, representatives of the A.A.P.T. on the Committee A.S.A. Z-58.
† Deceased.
[1] *Rev. Sci. Inst.* **7**, 332 (1936).
[2] ASA Z-10.4—1943 bottom of p. 18.
[3] *American Standard Definitions of Electrical Terms* (Amer. Inst. Elec. Eng. 1942). See items 55.10.025, 55.10.040, and 55.10.045.
[4] In view of the many distinct and confusing meanings attached to the word "intensity," as in intensity of magnetization and intensity of a wave, it also appears wise to avoid the use of intensity as in line 4 of Table I.
[5] Professor F. W. Sears, Massachusetts Institute of Technology, Cambridge, Mass.

AMERICAN JOURNAL OF PHYSICS VOLUME 18, NUMBER 3 MARCH, 1950

Letters to the Editor

An Elementary Demonstration on the Incompressibility of Water and the Elasticity of Glass

A VERY elementary but highly effective demonstration of the incompressibility of water and the elastic properties of glass is provided by the following: Equip a conventional whisky bottle (the flat kind, made of clear glass) with a tight-fitting, one-hole stopper into which is inserted a long glass tube with capillary bore. Fill the bottle with colored water and allow the initial water level to be somewhat above the stopper. Now grasp the bottle at the wide faces between thumb and finger and squeeze gently. A very appreciable rise in the liquid column is observed.

Now grasp the bottle at opposite edges and squeeze. A marked *depression* of the original level is observed. The volume of the bottle is obviously increased.

Before this last is done the class is asked what they think will happen. Very few expect a depression of the column.

The need for the right-shaped bottle is now obvious. A round one will not do so well.

JULIUS SUMNER MILLER

Dillard University
New Orleans, Louisiana

Resonant Response of a Tuning Fork

THE simple mechanism of resonant response is familiar. Two tuning forks of the same pitch, mounted on resonant boxes, are set some distance apart. One is struck and shortly silenced, whereupon the other is heard.[1] An interesting extension of this provides a little drama. Support a metal pendulum bob (aluminum is good) by a fine string so that the bob *just touches* one prong of the receiving fork. The response of the receiver puts the bob in motion and a substantial amplitude may be reached on critical adjustment of the length. The effect is dramatic and somewhat "spooky"!

JULIUS SUMNER MILLER

Dillard University
New Orleans, Louisiana

[1] Sutton, *Demonstration experiments in physics* (McGraw-Hill, 1938), S-115.

ANNOUNCEMENTS AND NEWS

Southern California Section

The regular fall meeting of the Southern California Section of the American Association of Physics Teachers was held in the Norman Bridge Laboratory of Physics at the California Institute of Technology in Pasadena on Saturday, October 22, 1949. One hundred and sixty members and guests attended the morning program, and one hundred and twenty-five of these stayed for the afternoon program. Between luncheon and the afternoon session most of the members enjoyed an inspection trip through the Analog Computer project on the Institute campus.

The morning program started with an invited paper by Professor Willard Geer of the University of Southern California on the subject, "Color television." Professor Geer discussed with considerable detail the three main, current methods of color televising, one method of which was by his own proposed three-gun tube. Professor Geer's talk was spiced throughout with interesting anecdotes of the recent hearings in Washington on color television before the FCC which Professor Geer had attended.

Following Professor Geer's invited paper, the following contributed papers were heard:

1. **A rangefinder using the eyes as objectives.** HARLEY J. HADEN, *Glendale College.*
2. **Wiener's experiment: Stationary or progressive waves?** JOSEPH W. ELLIS, *University of California at Los Angeles.*
3. **Education?—or merely training? VI.—Why continue teaching the parallelogram of forces principle?** GEORGE FORSTER, *Pasadena City College.*
4. **The paradox of minimum evaporation.** N. W. CUMMINGS.
5. **Some properties of real fluids.** GEORGE WOOLSEY, *East Los Angeles Junior College.*
6. **The old time classroom recitation—can it be restored?** LAURENCE E. DODD, *University of California at Los Angeles.*
7. **The value of absolute zero of temperature.** WALLACE R. MUELDER, *El Camino College.*
8. **A proof of Stokes' theorem.** EARL C. REX, *George Pepperdine College.*

The afternoon program consisted of an invited speech by Dr. Robert F. Bacher on the subject, "Science and atomic energy." This was especially valuable to the members of the Section because of Doctor Bacher's background as the sole scientific member of the Atomic Energy Commission before his resignation last spring to accept the chairmanship of the Division of Physics, Astrophysics, and Mathematics at the California Institute of Technology.

At a short business session following the afternoon program Professor David L. Soltau reported on the problems being currently discussed in the Executive Committee of AAPT. Following this report, Professor Soltau was re-elected as Section representative to the AAPT Executive Committee for the year 1950.

FOSTER STRONG, *Secretary*

Michigan Teachers of College Physics

Teachers of physics from Michigan colleges and universities met in Ann Arbor in the West Physics Building of the Department of Physics, University of Michigan, on Saturday, December 3, 1949. Dr. E. F. Barker presided over the sessions. A program of invited and contributed papers was presented as follows:

Observations on annihilation photons. J. R. BEYSTER, *University of Michigan.*
An apparatus for determining the expansivity of mercury. B. H. DICKINSON, *Michigan State College.*
A remark on Fermat's principle in optics. R. SCHLEGEL, *Michigan State College.*
A resumé of the problems of superconductivity. G. E. UHLENBECK, *University of Michigan.*
Discussion of visual education in general physics. Introduced by F. T. HAWLEY, *Muskegon Junior College.*
Demonstration: Soap bubble model of crystal structure. F. C. MOESEL, *University of Michigan, College of Engineering.*
Quadrupole energy of nuclei in crystals. C. KIKUCHI, *Michigan State College.*
Nonlinear circuits in junior electrical measurements. G. P. BREWINGTON, *Lawrence Institute of Technology.*

Luncheon was served at the Michigan League. At a brief business meeting it was decided to hold the spring (1950) meeting at Michigan State College, East Lansing, Michigan.

AMERICAN JOURNAL OF PHYSICS VOLUME 18, NUMBER 3 MARCH, 1950

New Members of the Association

The following persons have been made members or junior members (*J*) of the American Association of Physics Teachers since the publication of the preceding list [*Am. J. Physics* **18**, 118 (1950)].

Arvin, Martin J., Southern Illinois University, Carbondale, Ill.
Belser, Richard Baker, 1016 Rosedale Rd., N.E., Atlanta, Ga.
Blend, Harvey, Suffolk University, 20 Derne St., Boston, Mass.
Bullock, M. Loren, Swain Hall, Indiana University, Bloomington, Ind.
Burger, John M., Missouri School of Mines, Rolla, Mo.
Calhoun, John Decatur, Jr., Rt. 3, Box 129 A, Phoenix, Ariz.
Chang, Howard (How Chung), 27 South St., Malone, N. Y.
Critchfield, Ted Eldon (*J*), 2246 Waltonia Dr., Montrose, Calif.
Davis, Orla Aldis, Salem, W. Va.

Defoe, Ona Kenneth, 4588 Parkview Pl., St. Louis 10, Mo.
Dillaha, Isham Wesley, Box 113, Arkansas Tech., Russellville, Ark.
Dittberner, Donald Lloyd (*J*), Stimson Hall, Pullman, Wash.
Dixon, Dwight R., 1315 Spruce St., Berkeley 9, Calif.
Duncan, Donald Stuart, Pratt Institute, Brooklyn 5, N. Y.
Eggenberger, Delbert N., Chem. Res. and Dev. Dept., Armour & Co., Union Stock Yards, Chicago 9, Ill.
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There are . . . some minds which can go on contemplating with satisfaction pure quantities presented to the eye by symbols, and to the mind in a form which none but mathematicians can conceive.

There are others who feel more enjoyment in following geometrical forms which they draw on paper, or build up in the empty space before them.

Others, again, are not content unless they can project their whole physical energies into the scene which they conjure up. They learn at what rate the planets rush through space, and they experience a delightful feeling of exhilaration. They calculate the forces with which the heavenly bodies pull on one another, and they feel their own muscles straining with the effort.

To such men momentum, energy, mass are not mere abstract expressions of the results of scientific enquiry. They are words of power, which stir their souls like the memories of childhood.

For the sake of persons of these different types, scientific truth should be presented in different forms, and should be regarded as equally scientific, whether it appears in the robust form and the vivid colouring of a physical illustration, or in the tenuity and paleness of a symbolical expression.—JAMES CLERK MAXWELL (Quoted in *Nuclear Physics in Photographs* by C. F. POWELL and G. P. S. OCCHIALINI).